

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

TECHNICAL NOTE 4265

COMPOSITION AND THERMODYNAMIC PROPERTIES OF AIR IN CHEMICAL EQUILIBRIUM

By W. E. Moeckel and Kenneth G. Weston

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Cleveland, Ohio



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OF AIR IN CHEMICAL EQUILIBRIUM

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SUMMARY

Charts have been prepared relating the thermodynamic properties of air in chemical equilibrium for temperatures to 15,000° K and for pressures from 10^{-5} to 10^{+4} atmospheres. Also included are charts showing the composition of air, the isentropic exponent, and the speed of sound. These charts are based on thermodynamic data calculated by the National Bureau of Standards.

INTRODUCTION

The properties of argon-free air in chemical equilibrium, based on the latest information on the thermodynamic constants for air, are presented in tabular form in reference 1. For convenience in handling computations involving the dynamics of air in equilibrium, these data have been prepared in chart form. The information contained in these charts duplicates the data contained in the Mollier diagram of reference 2, but the present form of the charts may be more convenient for many purposes.

SYMBOLS

- a speed of sound, ft/sec
- g gravitational constant, 32.17 ft/sec²
- h enthalpy, Btu/lb; h = 0 for molecular air at 0° K
- J mechanical equivalent of heat, 778 ft-lb/Btu
- M molecular weight of mixture
- M_i molecular or atomic weight of the i^{th} constituent

M_0	molecular weight of undissociated air, 28.966 for the composition used
p	pressure, atm
R	gas constant, $1.987 \frac{\text{Btu}}{\text{mole-}^\circ\text{R}}$
S	entropy, $\frac{\text{Btu}}{(\text{Initial mole of air})(^\circ\text{R})}$
T	temperature (consistent units)
T_0	reference temperature, 273.16°K
v_i	volume fraction of i^{th} constituent
w_i	weight fraction of i^{th} constituent
y_i	concentration of i^{th} constituent, number of particles per atom of air
z	$\frac{M_0}{M} = \frac{pM_0}{\rho RT}$
γ	local isentropic exponent
ρ	density, lb/cu ft
ρ_0	reference density, 0.0807 lb/cu ft

DESCRIPTION OF CHARTS

The equilibrium composition of air for temperatures to $24,000^\circ \text{K}$ and for densities from 10^{-6} to 10 times the reference density is shown in figure 1, which was constructed from data in reference 3. The composition is given in terms of the number of particles per atom of air. This number times 1.991 is the number of particles per undissociated molecule of air. The factor is 1.991 instead of 2.0 because argon is included in the composition assumed in reference 3. The volume fraction is

$$v_i = \frac{y_i}{\sum_1 y_i} \quad (1)$$

where y_i is the ordinate of figure 1 for the i^{th} constituent. The molecular-weight ratio in terms of y_i is

$$\frac{\mathcal{M}_0}{\mathcal{M}} = Z = 1.991 \sum_i y_i \quad (2)$$

Thus, in terms of y_i and Z , the volume fraction is

$$v_i = \frac{1.991 y_i}{Z} \quad (3)$$

The weight fraction of each constituent is given by

$$w_i = 1.991 y_i \frac{\mathcal{M}_i}{\mathcal{M}_0} \quad (4)$$

Figure 2 is a key to the thermodynamic charts, showing the range of pressures and enthalpies found in each chart. The charts themselves are presented in figure 3. These thermodynamic charts, in contrast to the composition charts, are for air free of argon and carbon dioxide.

For convenience, data from reference 4 were used to extend the charts down to a temperature of 200°K in the range of pressures from 10^{-2} to 10^{+2} atmospheres. Furthermore, perfect-gas relations were used to complete the region below 2000°K between 10^{-5} and 10^{-2} atmosphere on chart 1 of figure 3.

Included on these plots of enthalpy against pressure are lines of constant S/R , constant temperature, and constant molecular-weight ratio Z . Constant-density lines are not included. The density can be computed from the equation of state:

$$\rho = \frac{p\mathcal{M}}{RT} = \frac{p\mathcal{M}_0}{ZRT} \quad (5)$$

For ρ in pounds per cubic foot, p in atmospheres, and T in $^\circ \text{R}$,

$$\rho = 39.65 \frac{p}{ZT} \quad (6)$$

The speed of sound can be calculated from

$$a^2 = \frac{\gamma g J T}{\mathcal{M}} = \frac{R}{\mathcal{M}_0} \gamma Z T g J \quad (7)$$

For a in feet per second and T in $^{\circ}\text{R}$, this becomes

$$a = 41.43 \sqrt{\gamma Z T} \quad (8)$$

The quantity γ is the derivative of $\log p$ with respect to $\log \rho$ along the local isentrope, and is the local isentropic exponent. This exponent is replotted (from ref. 5) in figure 4 as a function of enthalpy for several values of S/R . The speed of sound calculated from equation (8) is plotted in figure 5 as a function of temperature for several pressures.

Lewis Flight Propulsion Laboratory
National Advisory Committee for Aeronautics
Cleveland, Ohio, February 6, 1958

REFERENCES

1. Hilsenrath, Joseph, and Beckett, Charles W.: Tables of Thermodynamic Properties of Argon-Free Air to 15,000 $^{\circ}$ K. TN 56-12, Arnold Eng. Dev. Center, Sept. 1956.
2. Feldman, Saul: Hypersonic Gas Dynamic Charts for Equilibrium Air. Avco Res. Lab., Jan. 1957.
3. Gilmore, F. R.: Equilibrium Composition and Thermodynamic Properties of Air to 24,000 $^{\circ}$ K. Rep. 1543, Rand Corp., Aug. 24, 1955.
4. Hilsenrath, Joseph, et al.: Tables of Thermal Properties of Gases. Cir. 564, NBS, Nov. 1, 1955.
5. Moeckel, W. E.: Oblique-Shock Relations at Hypersonic Speeds for Air in Chemical Equilibrium. NACA TN 3895, 1957.

Note: To obtain particles per initial molecule of air, multiply ordinate by 1.891.

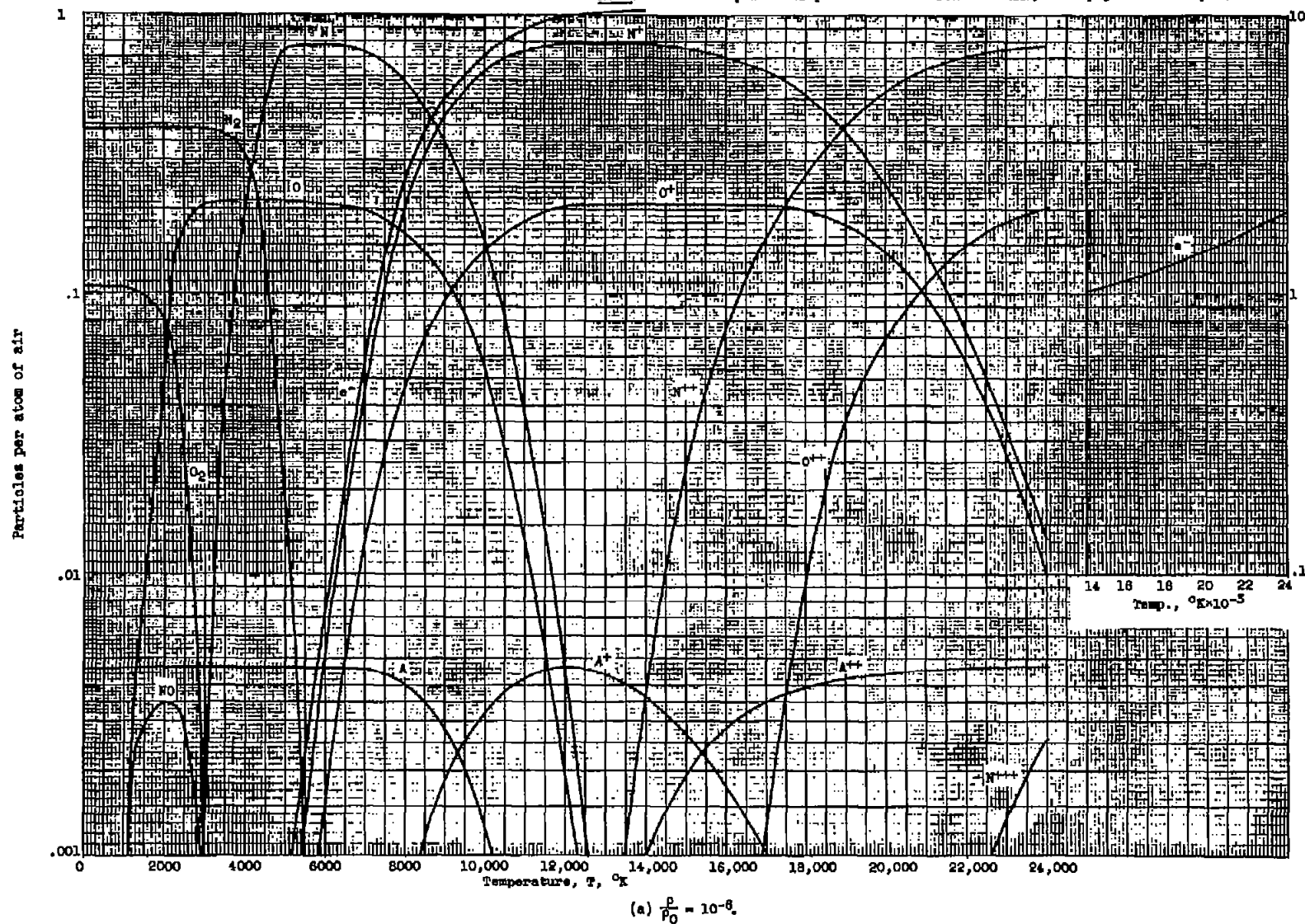


Figure 1. - Equilibrium composition of air to 24,000° K.

Note: To obtain particles per initial molecule of air, multiply ordinate by 1.981.

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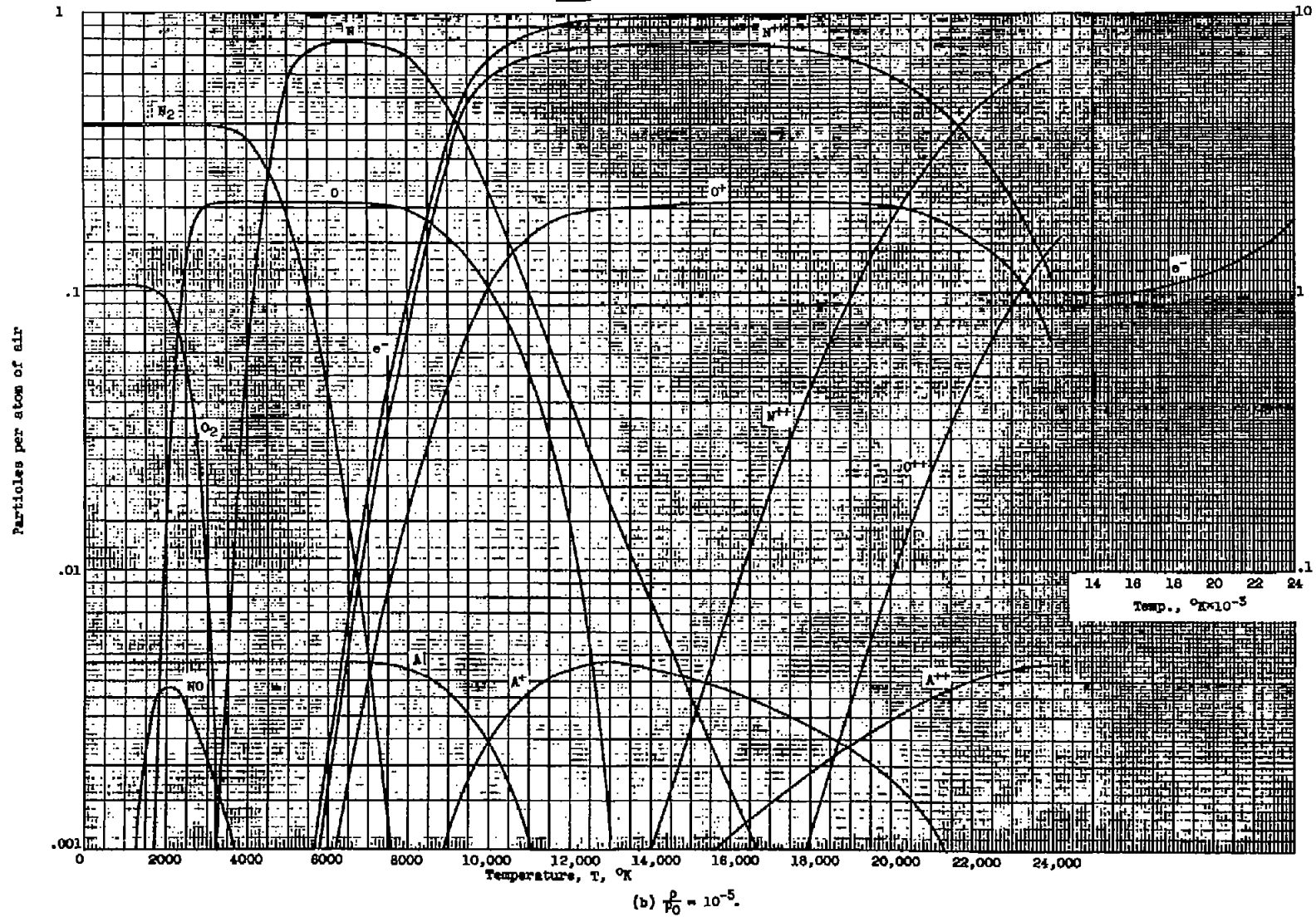


Figure 1. - Continued. Equilibrium composition of air to 24,000° K.

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Note: To obtain particles per initial molecule of air, multiply ordinate by 1.991.

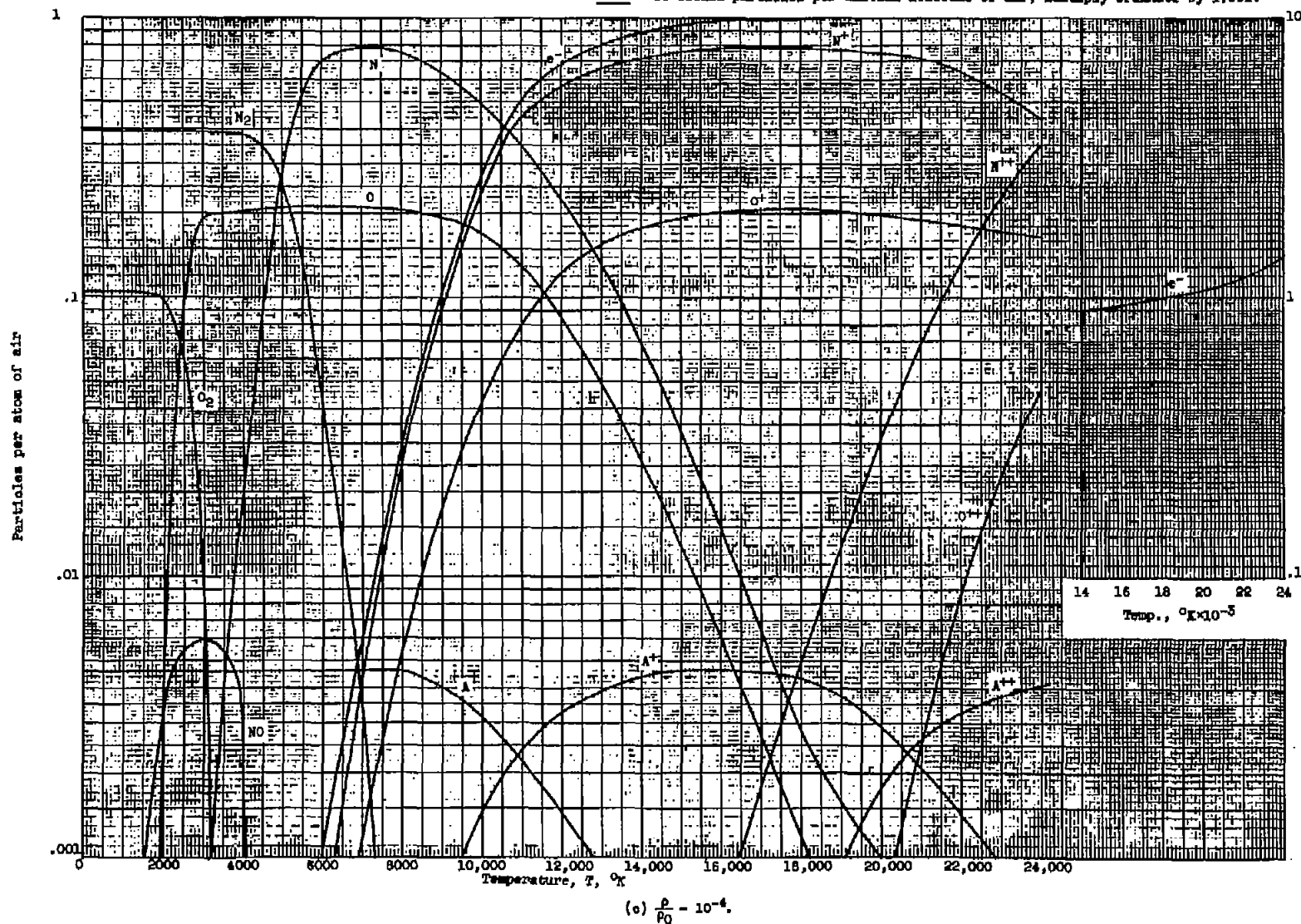


Figure 1. - Continued. Equilibrium composition of air to 24,000° K.

Note: To obtain particles per initial molecule of air, multiply ordinate by 1.931.

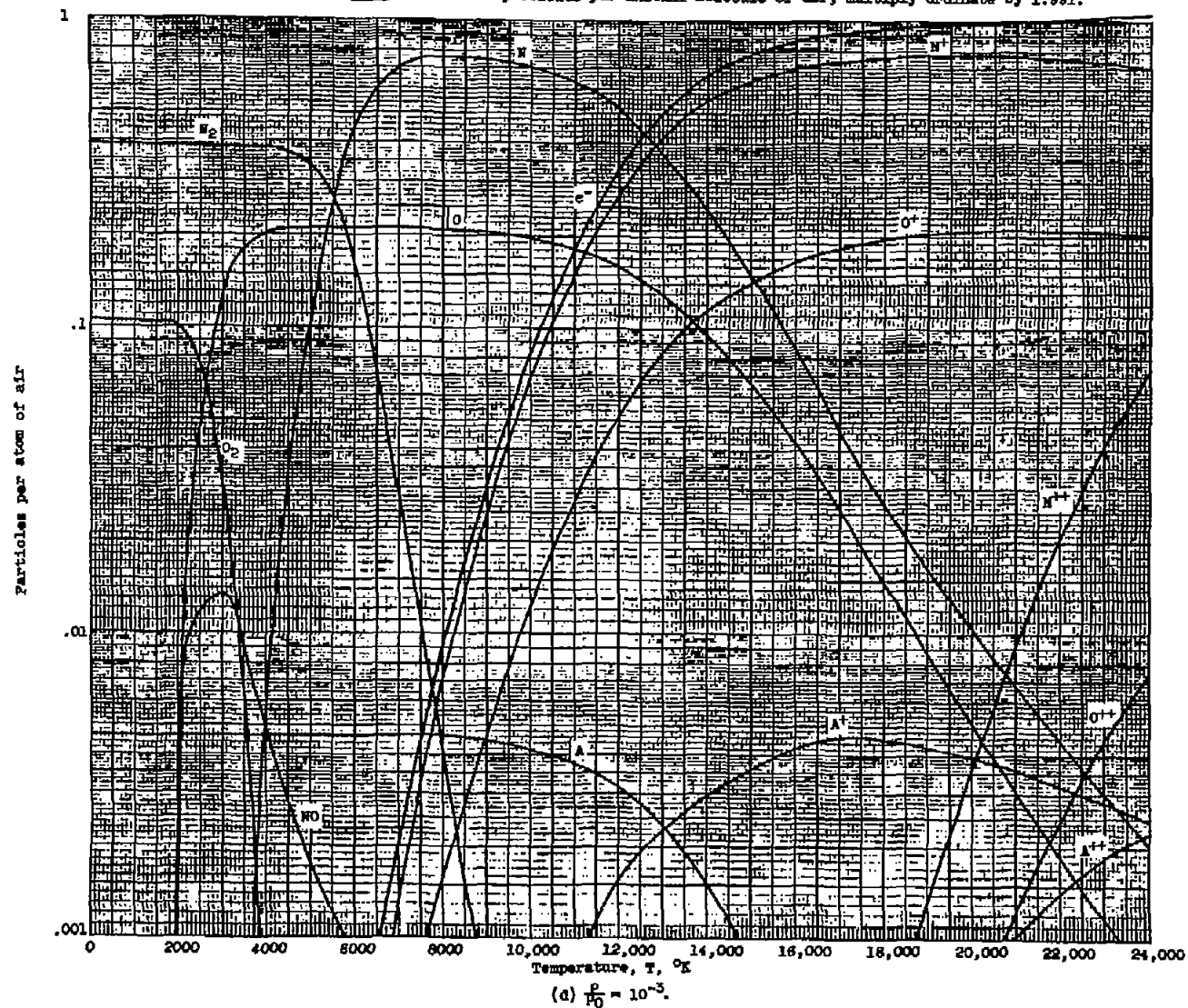


Figure 1. - Continued. Equilibrium composition of air to 24,000° K.

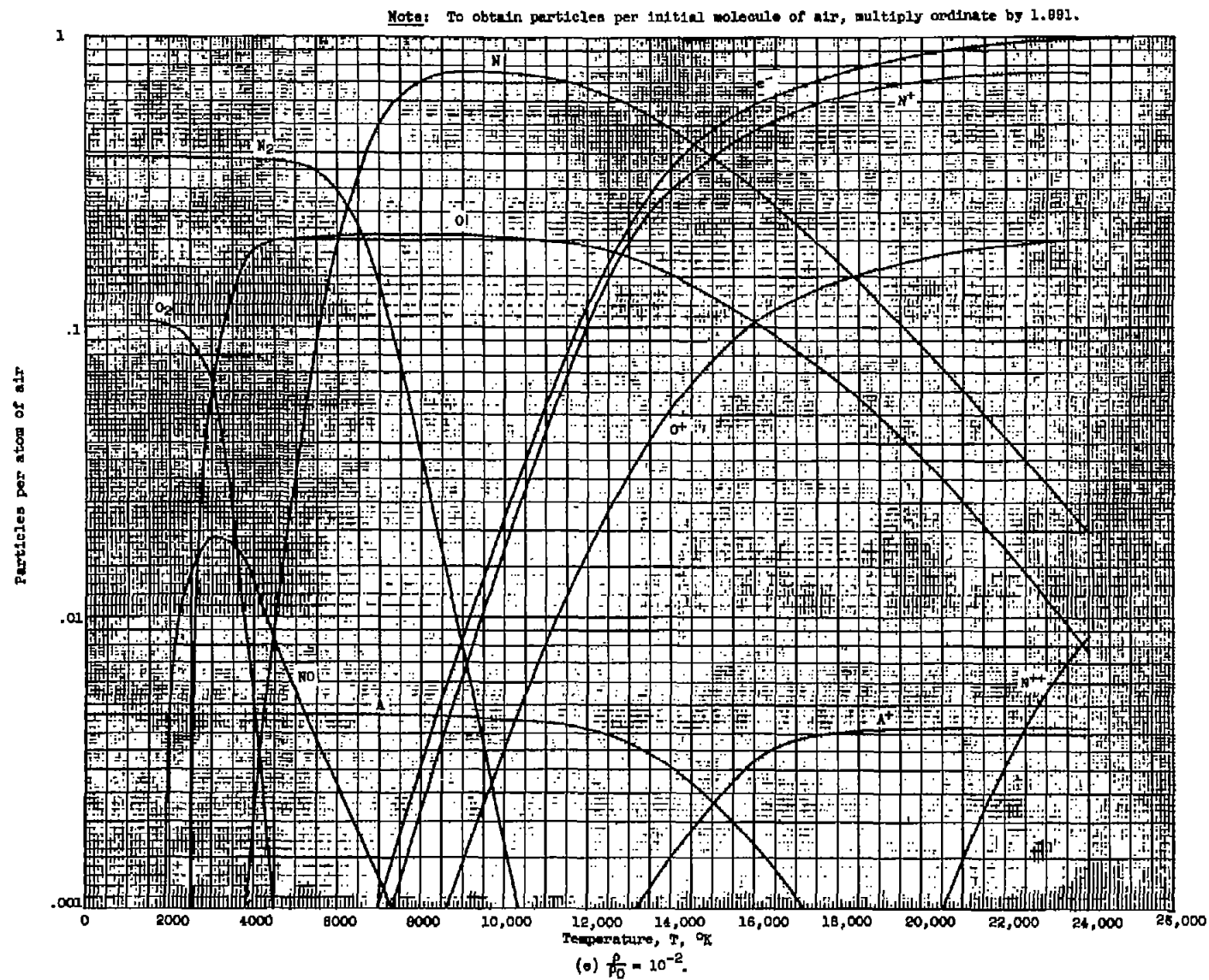


Figure 1. - Continued. Equilibrium composition of air to 24,000° K.

Note: To obtain particles per initial molecule of air, multiply ordinate by 1.981.

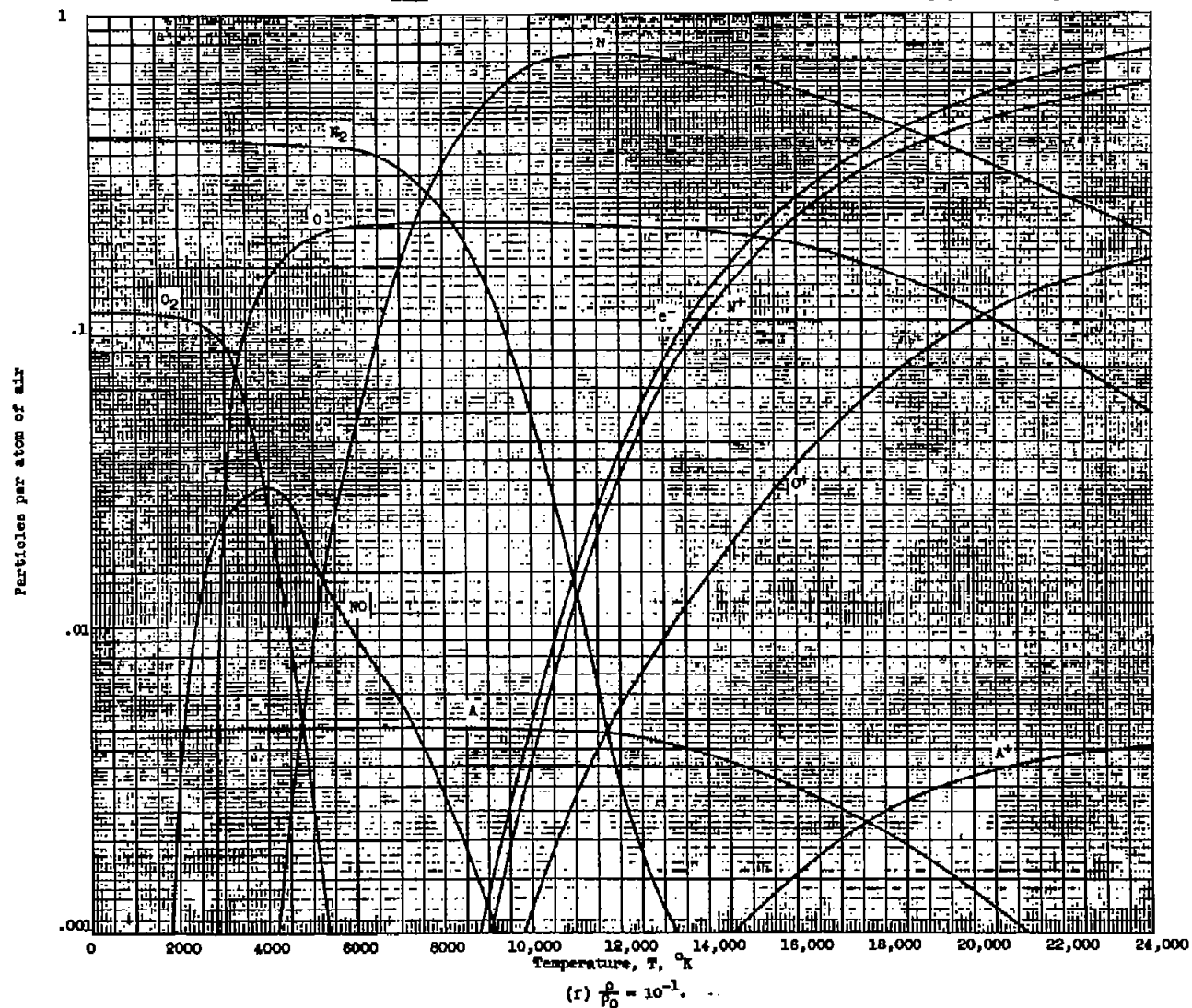


Figure 1. - Continued. Equilibrium composition of air to 24,000° K.

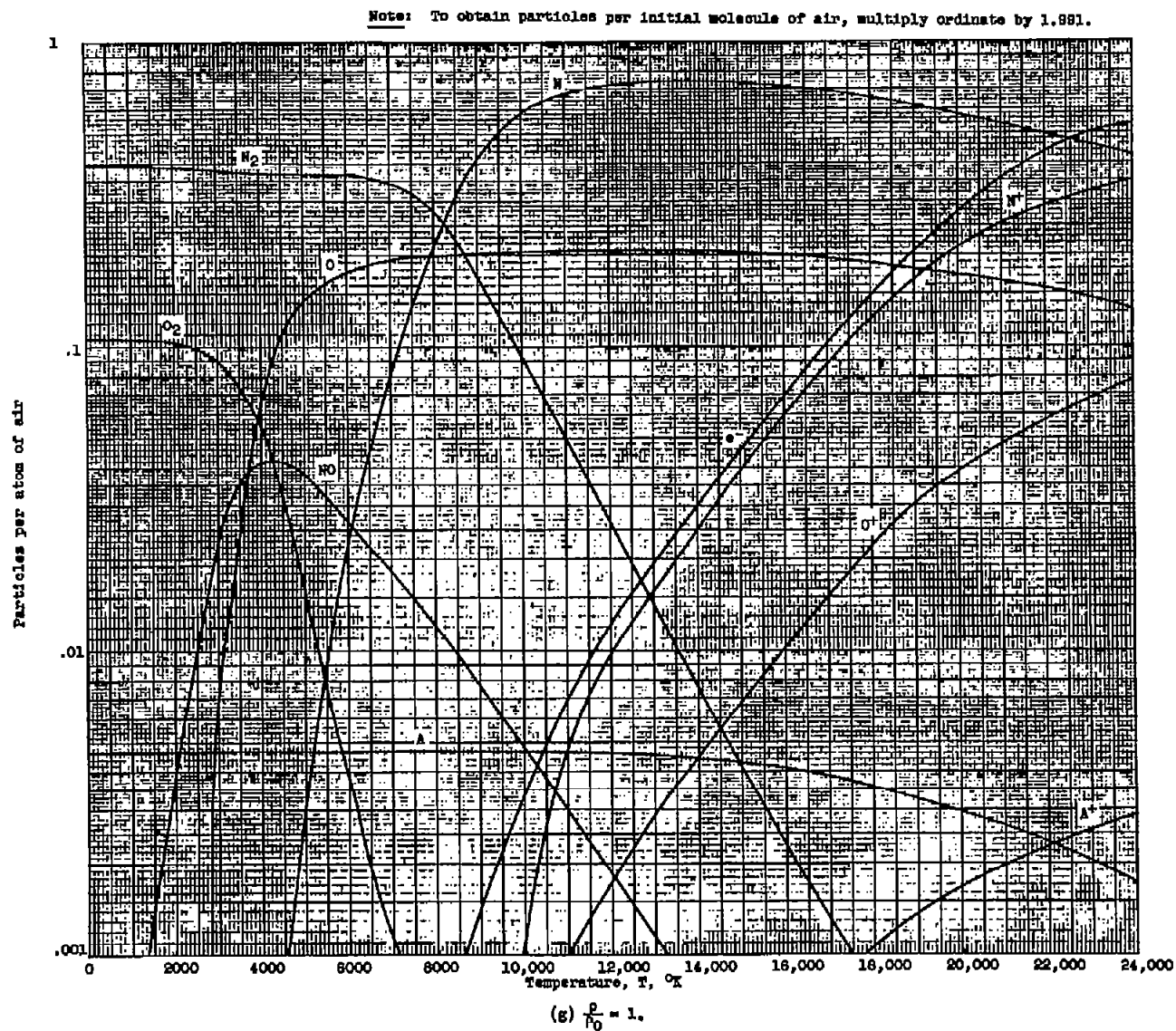


Figure 1. - Continued. Equilibrium composition of air to 24,000° K.

Note: To obtain particles per initial molecule of air, multiply ordinate by 1.981.

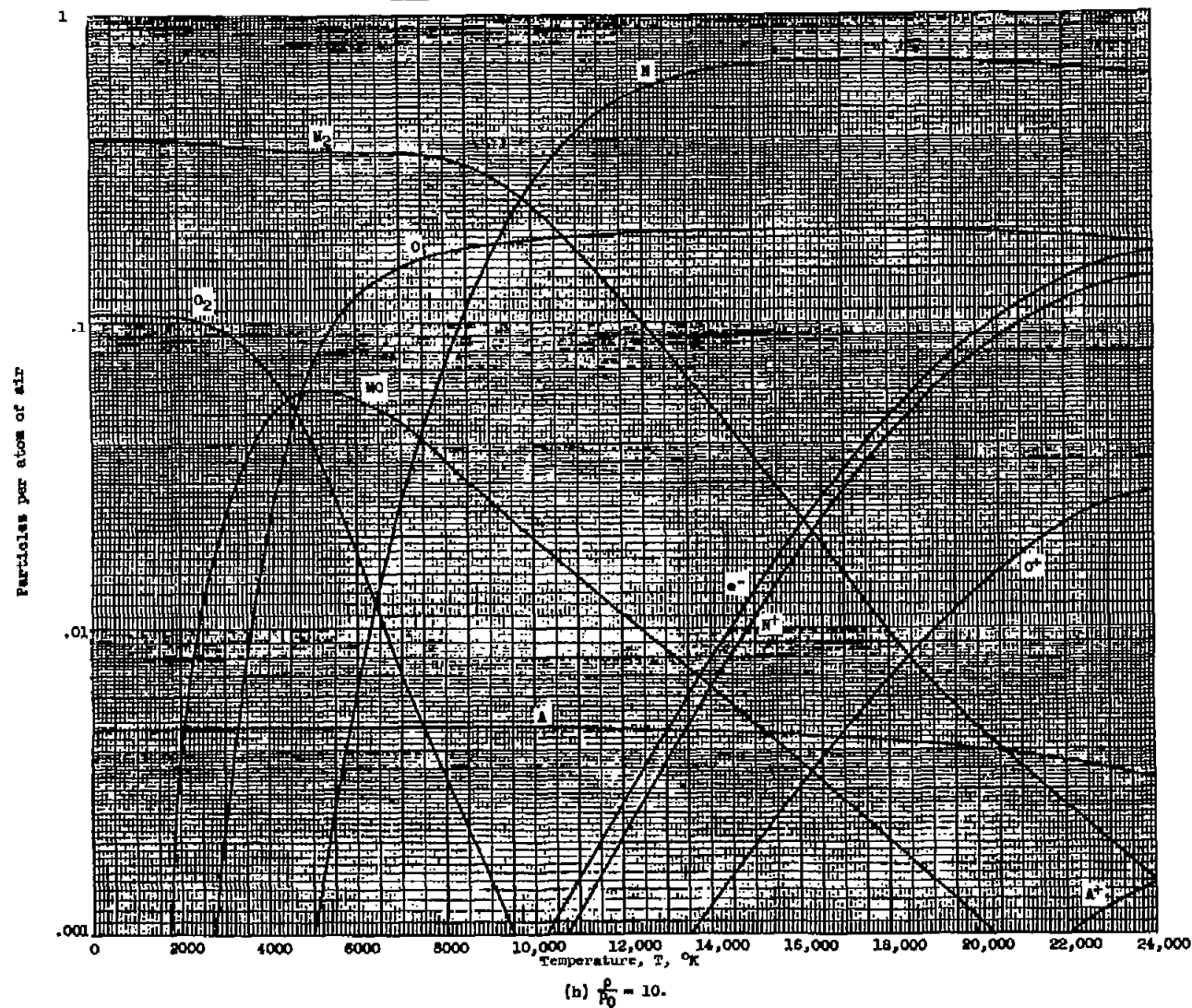


Figure 1. - Concluded. Equilibrium composition of air to 24,000° K.

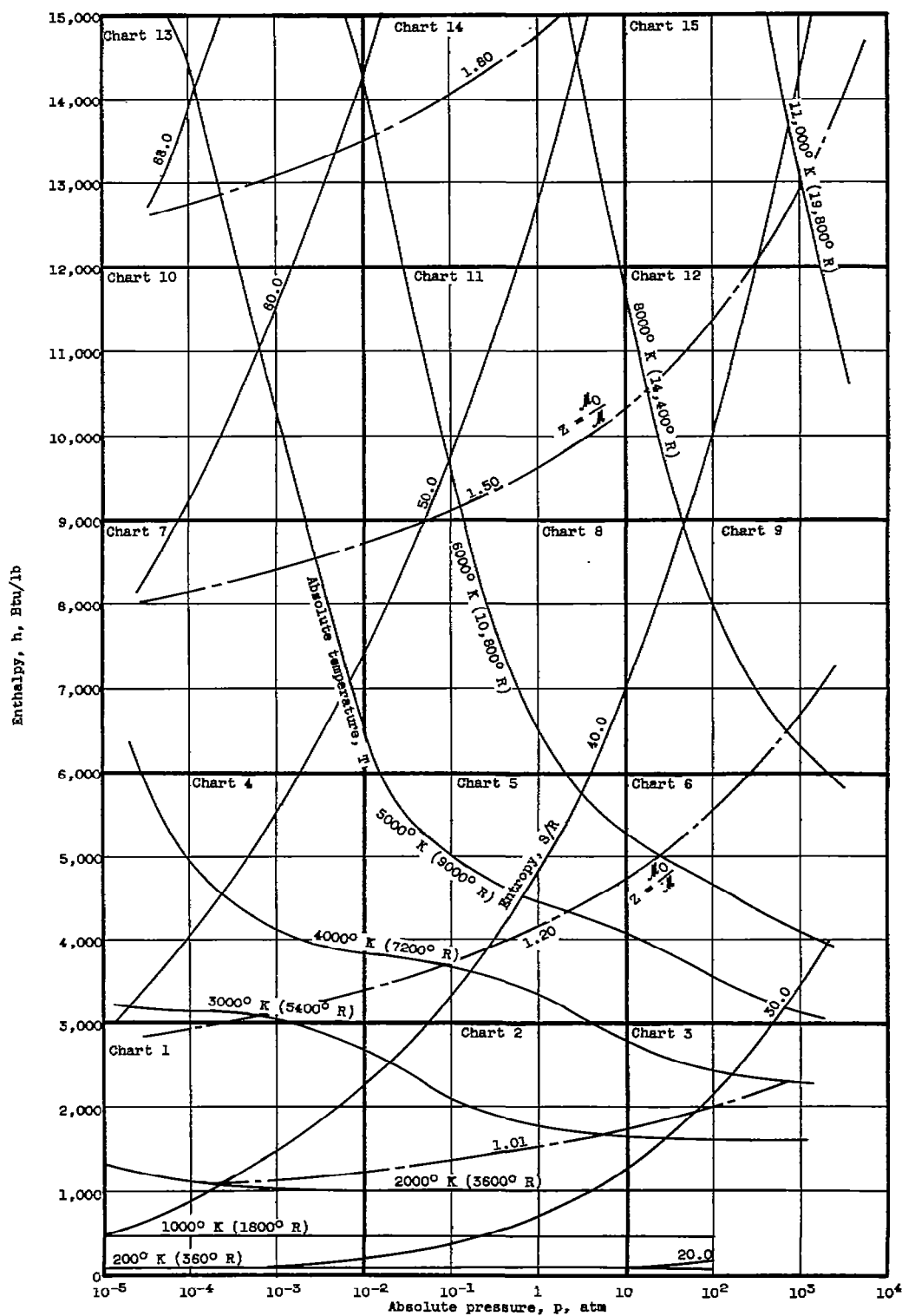


Figure 2. - Key to thermodynamic charts for air.

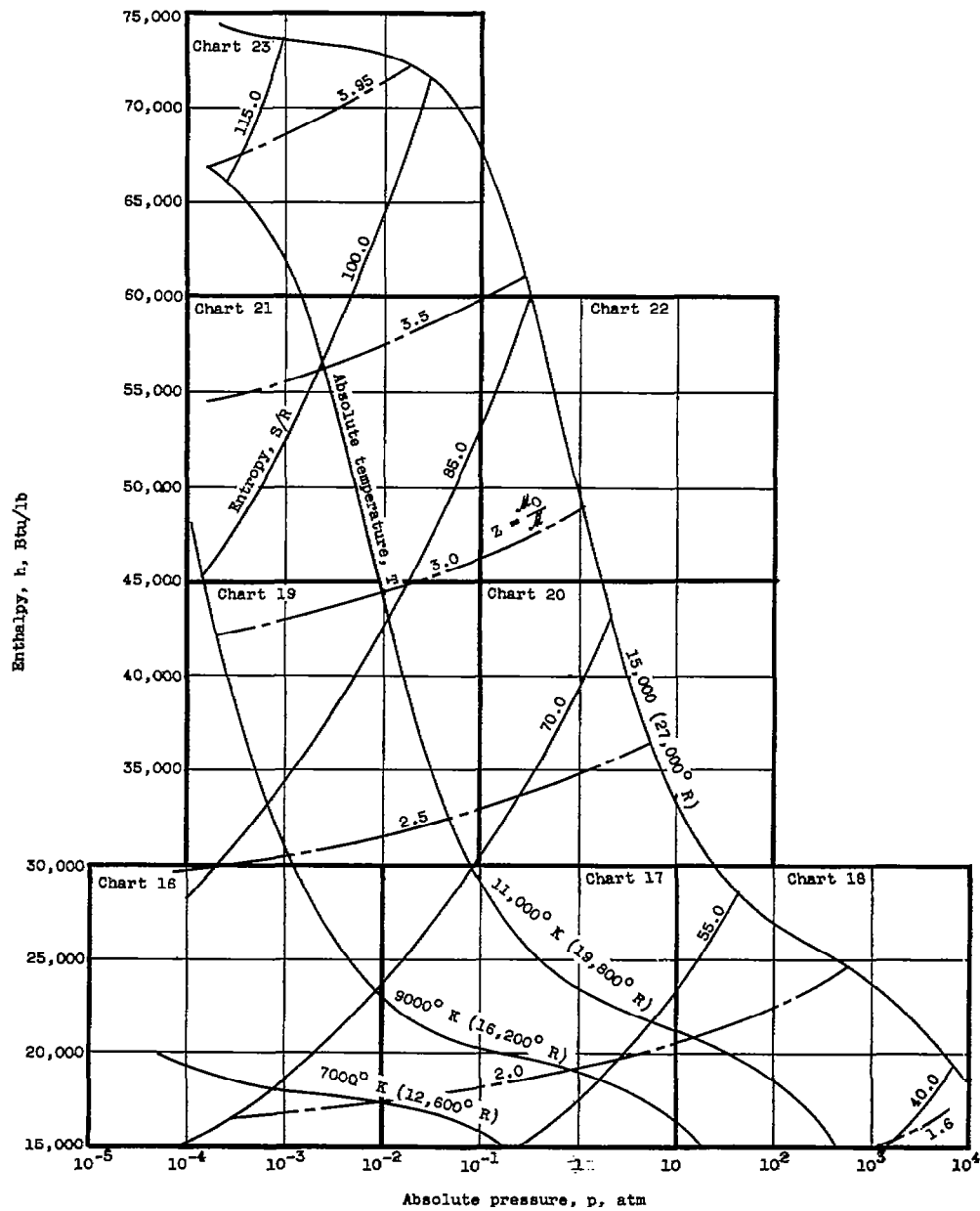
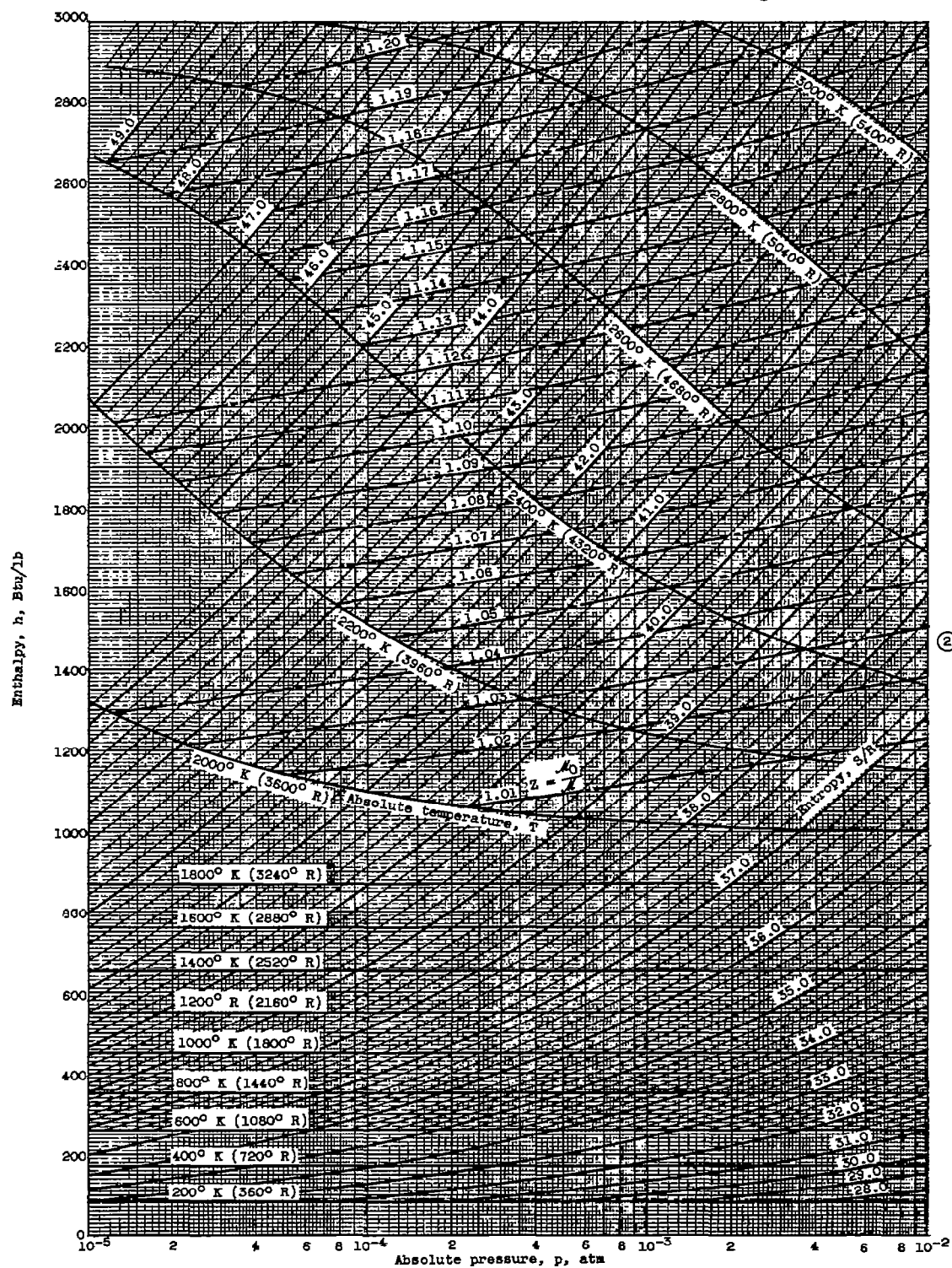
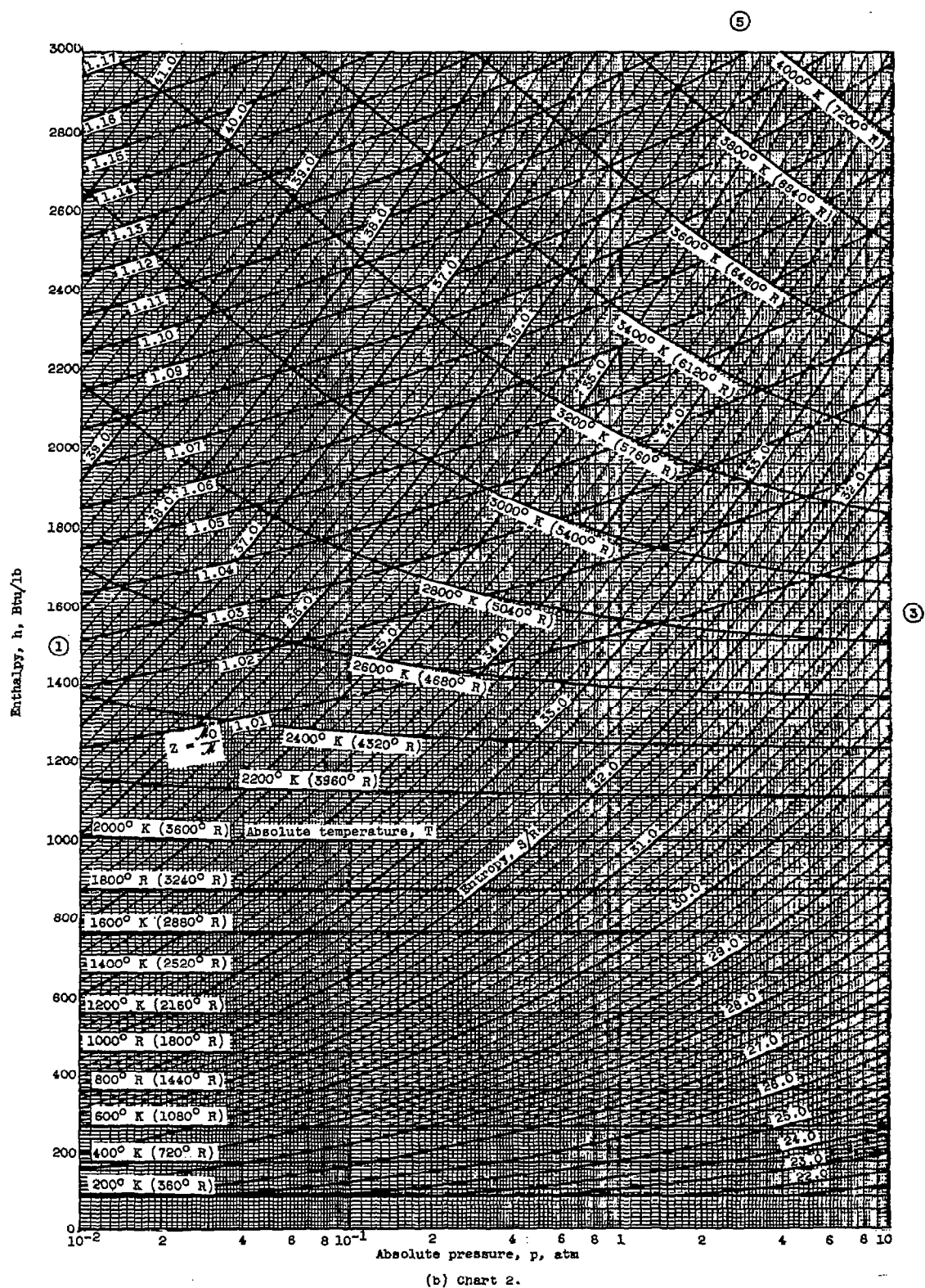


Figure 2. - Concluded. Key to thermodynamic charts for air.



(a) Chart 1.

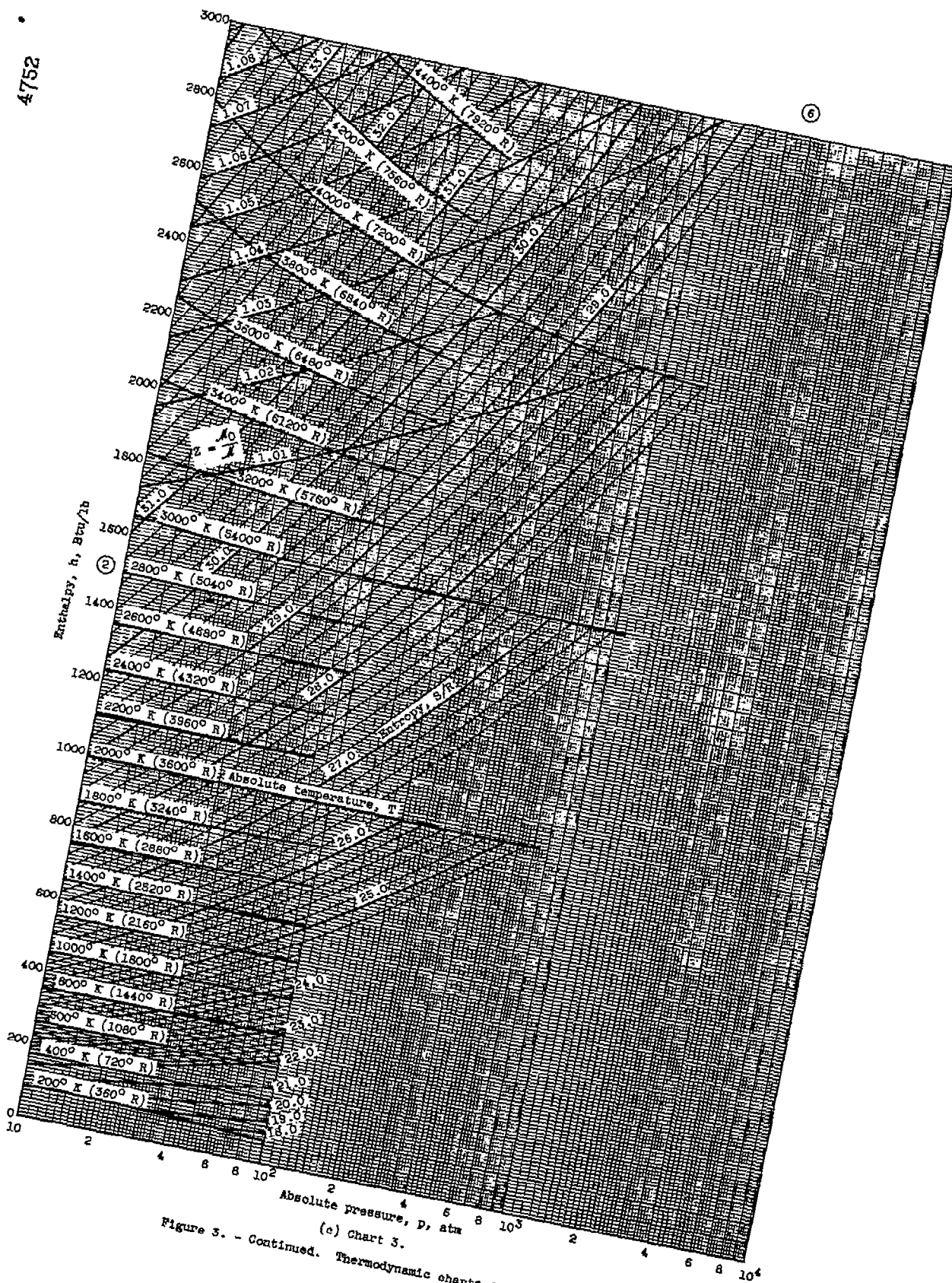
Figure 3. - Thermodynamic charts for air.

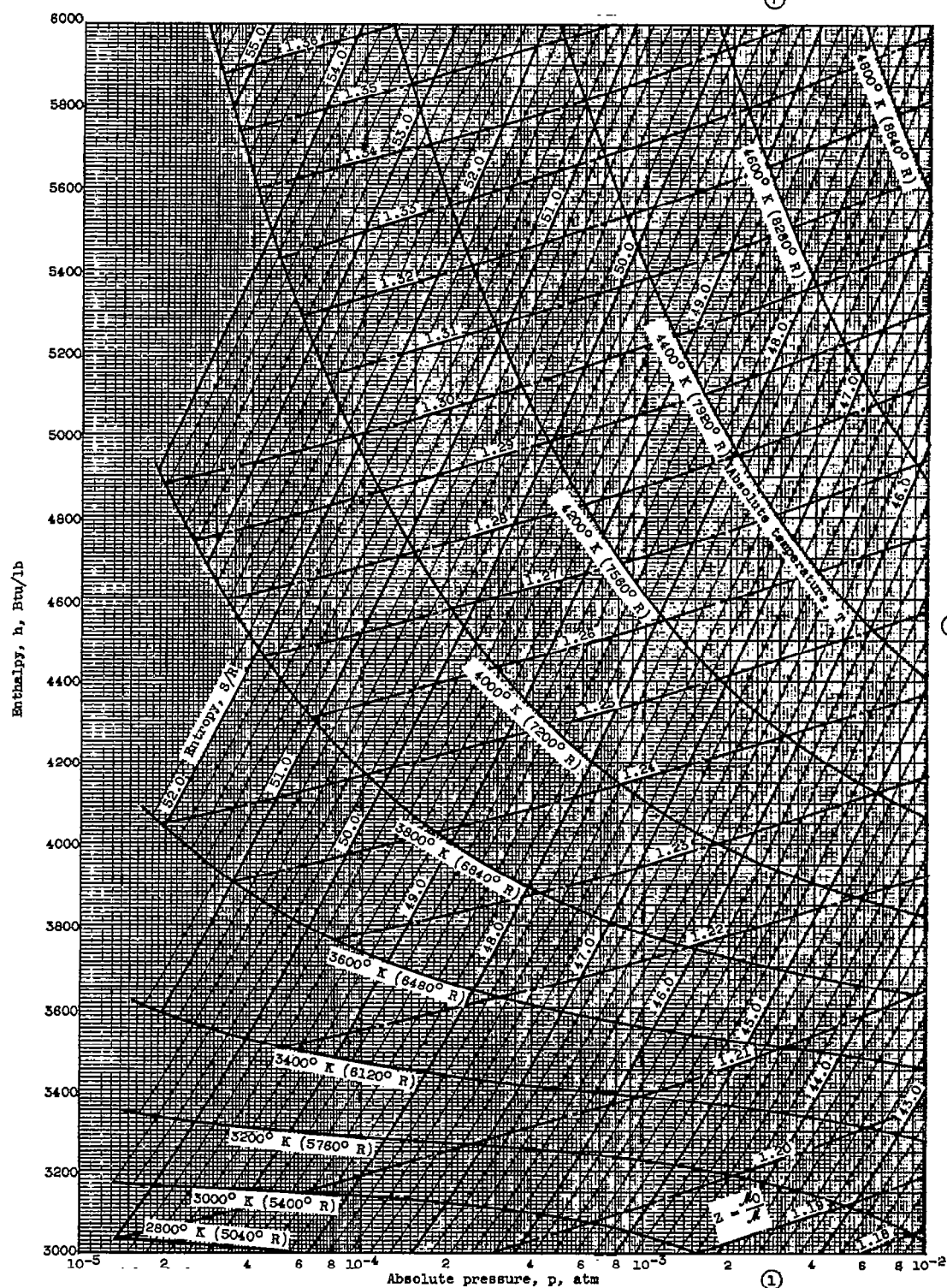


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(d) Chart 4.

Figure 3. - Continued. Thermodynamic charts for air.

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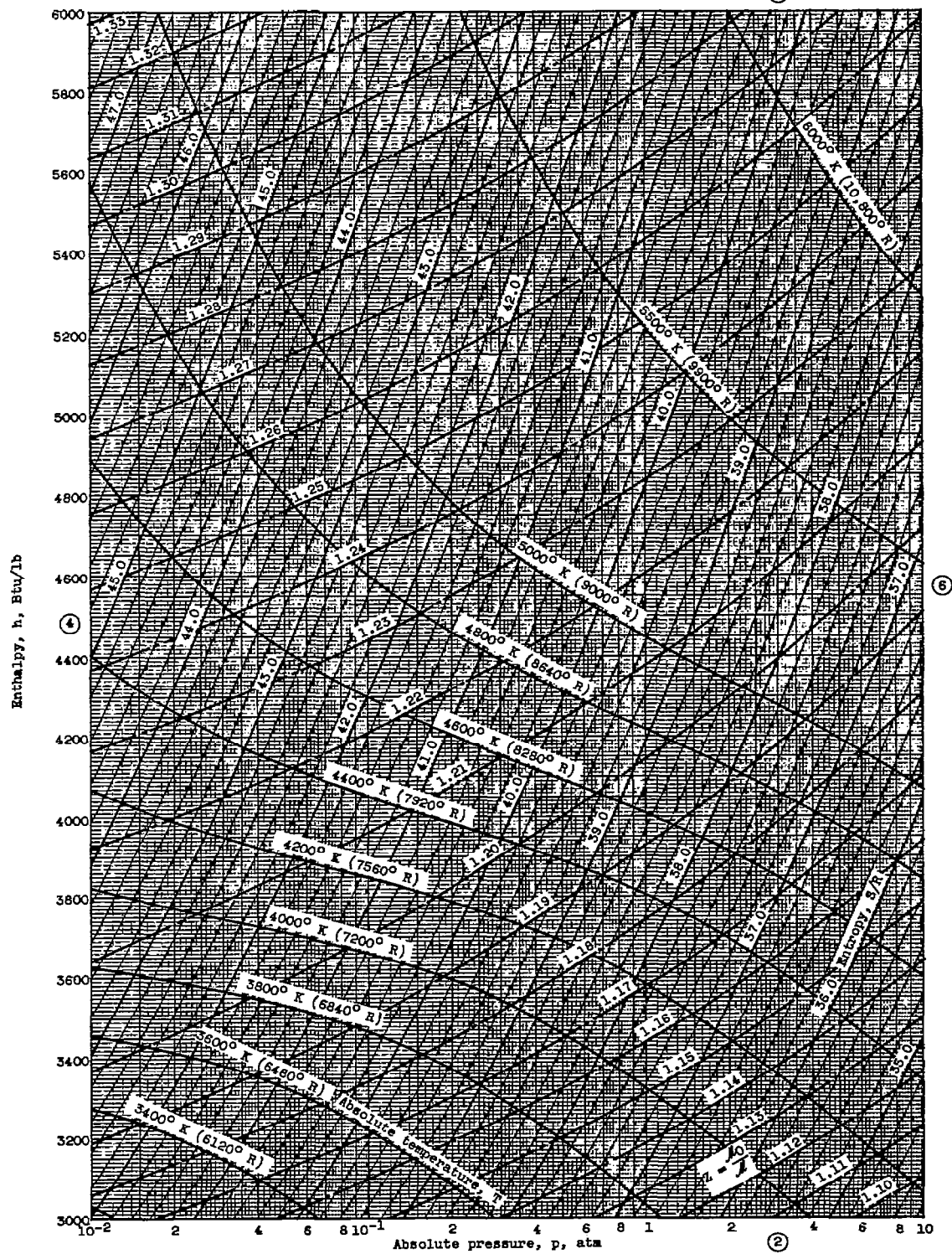
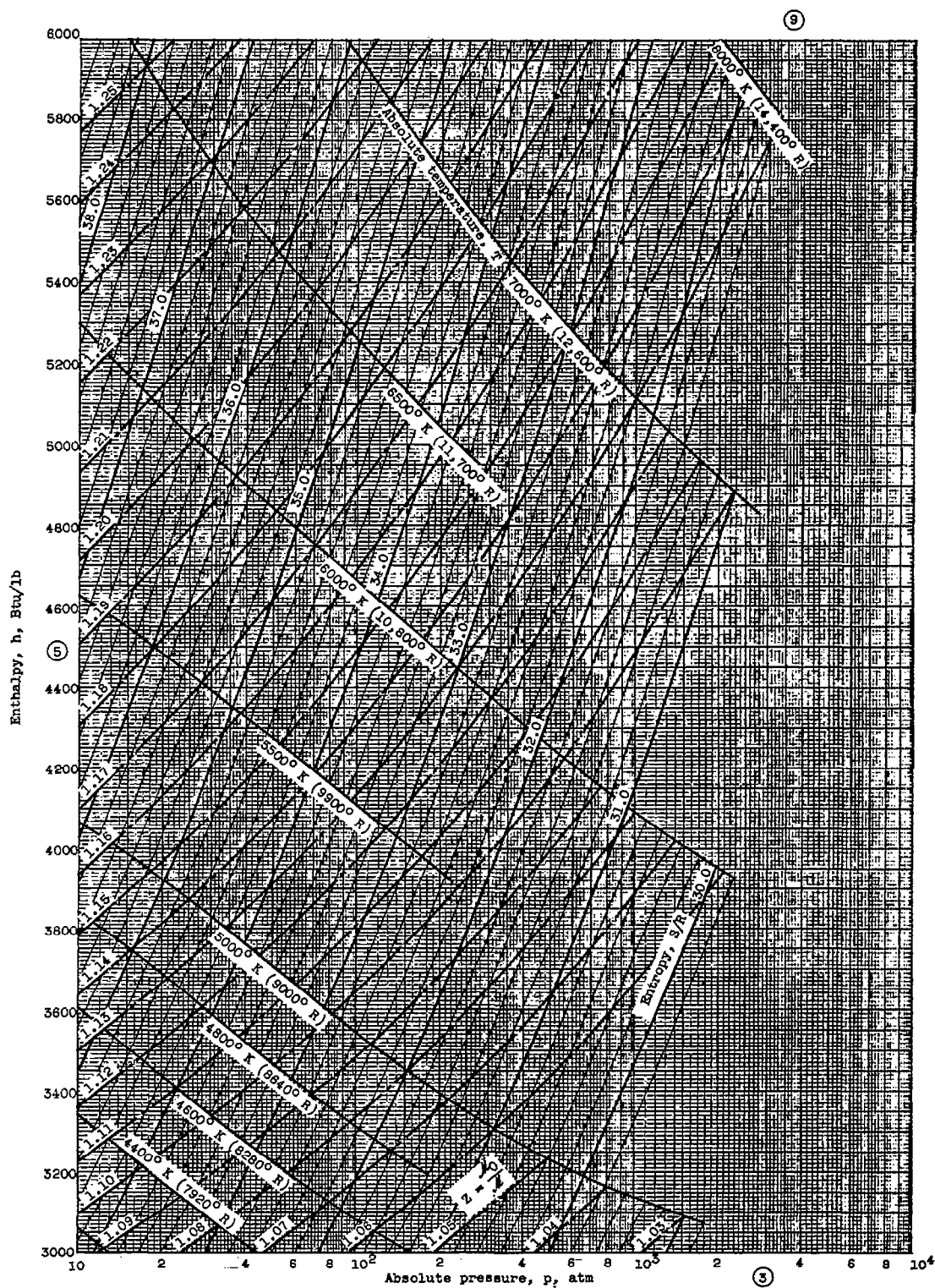
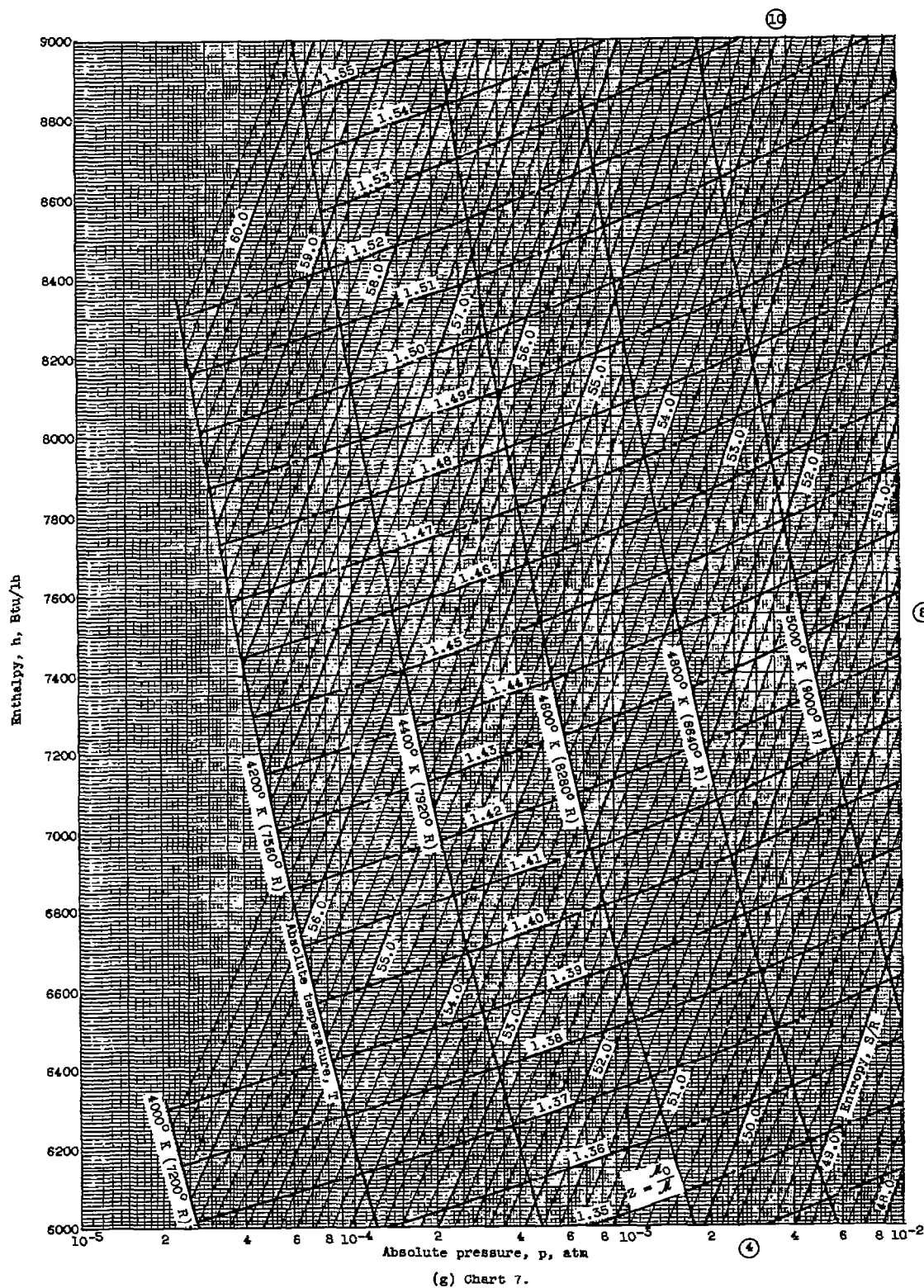


Figure 3. - Continued. Thermodynamic charts for air.





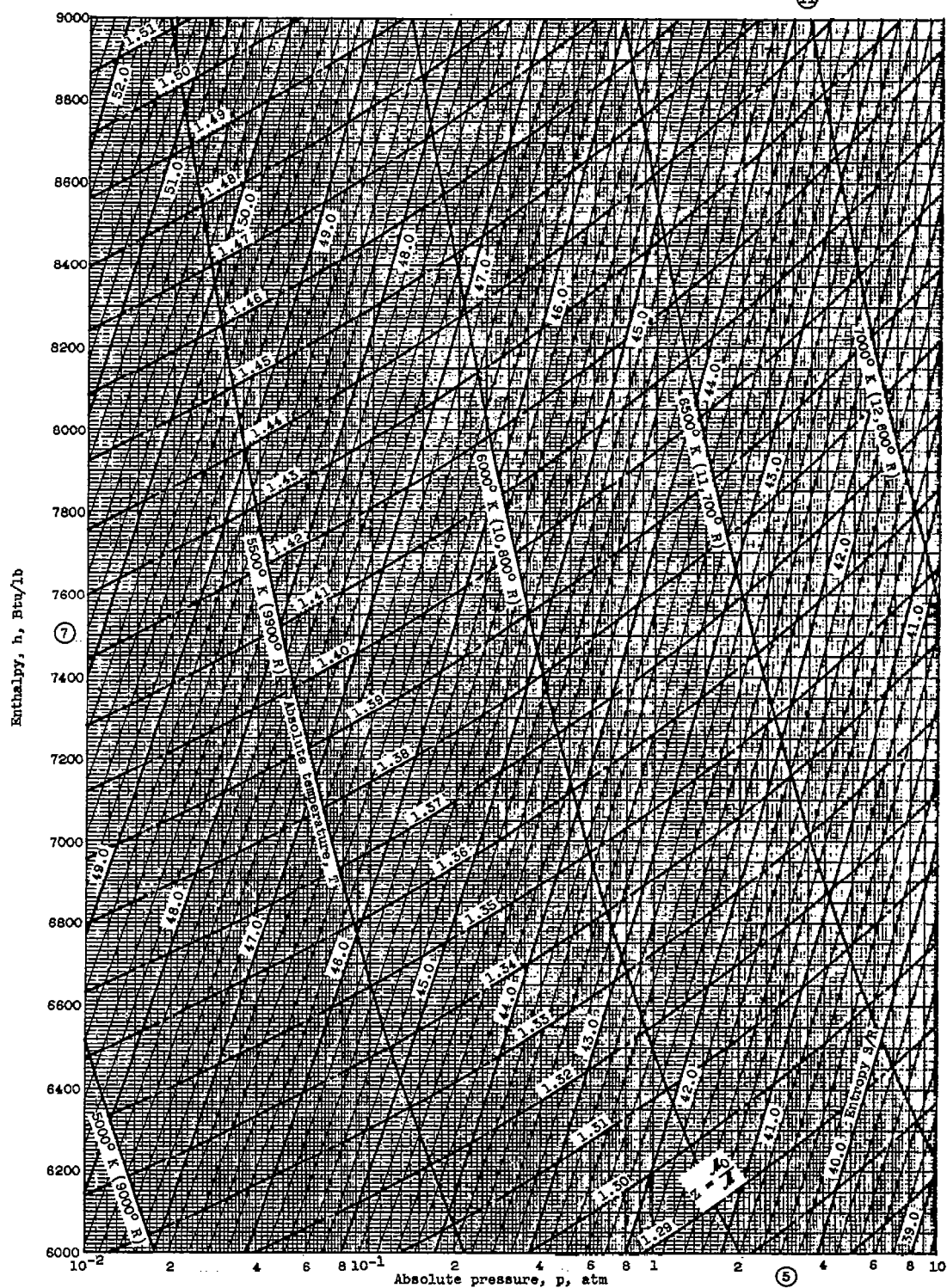


Figure 3. - Continued. Thermodynamic charts for air.

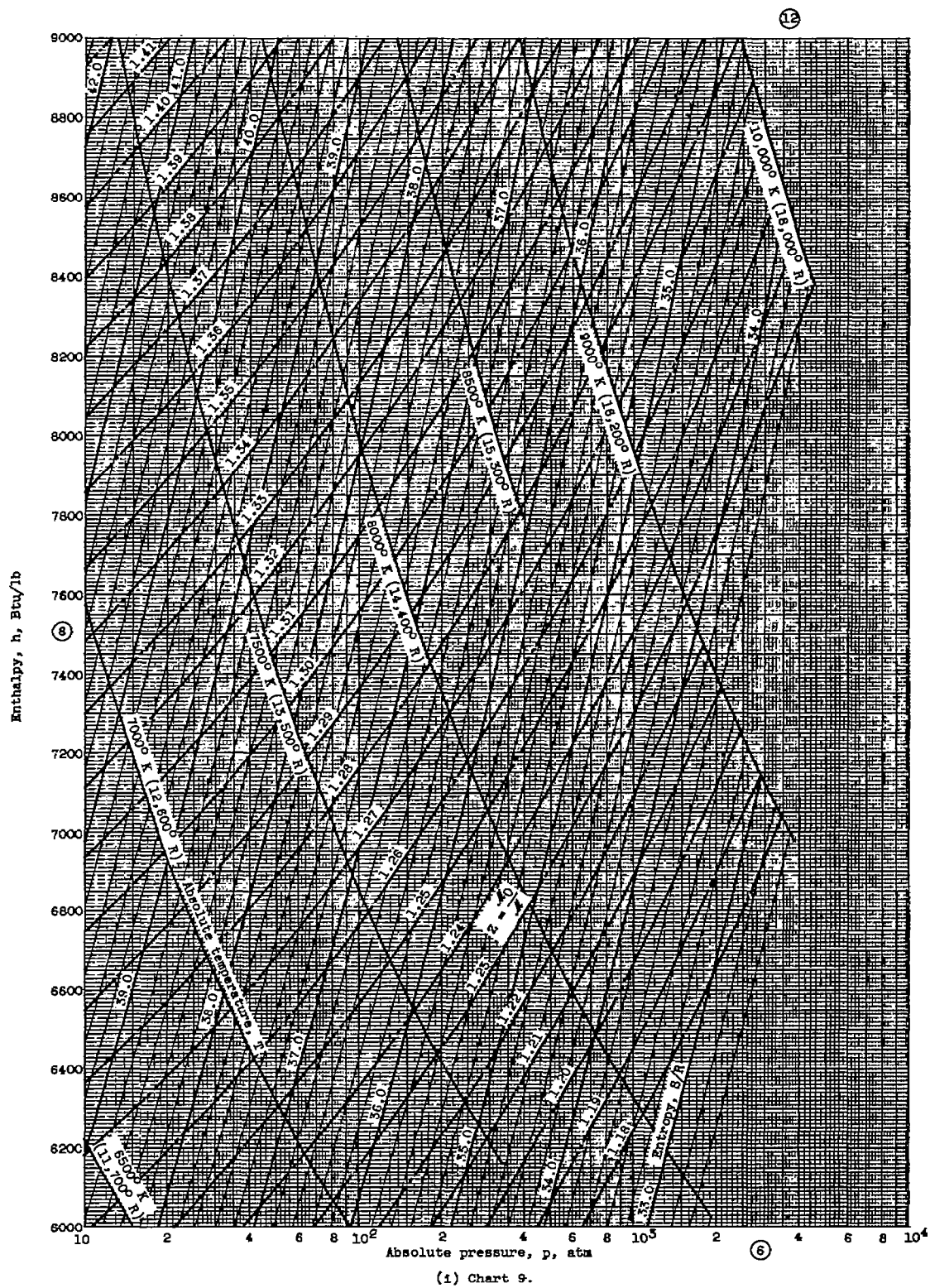


Figure 3. - Continued. Thermodynamic charts for air.

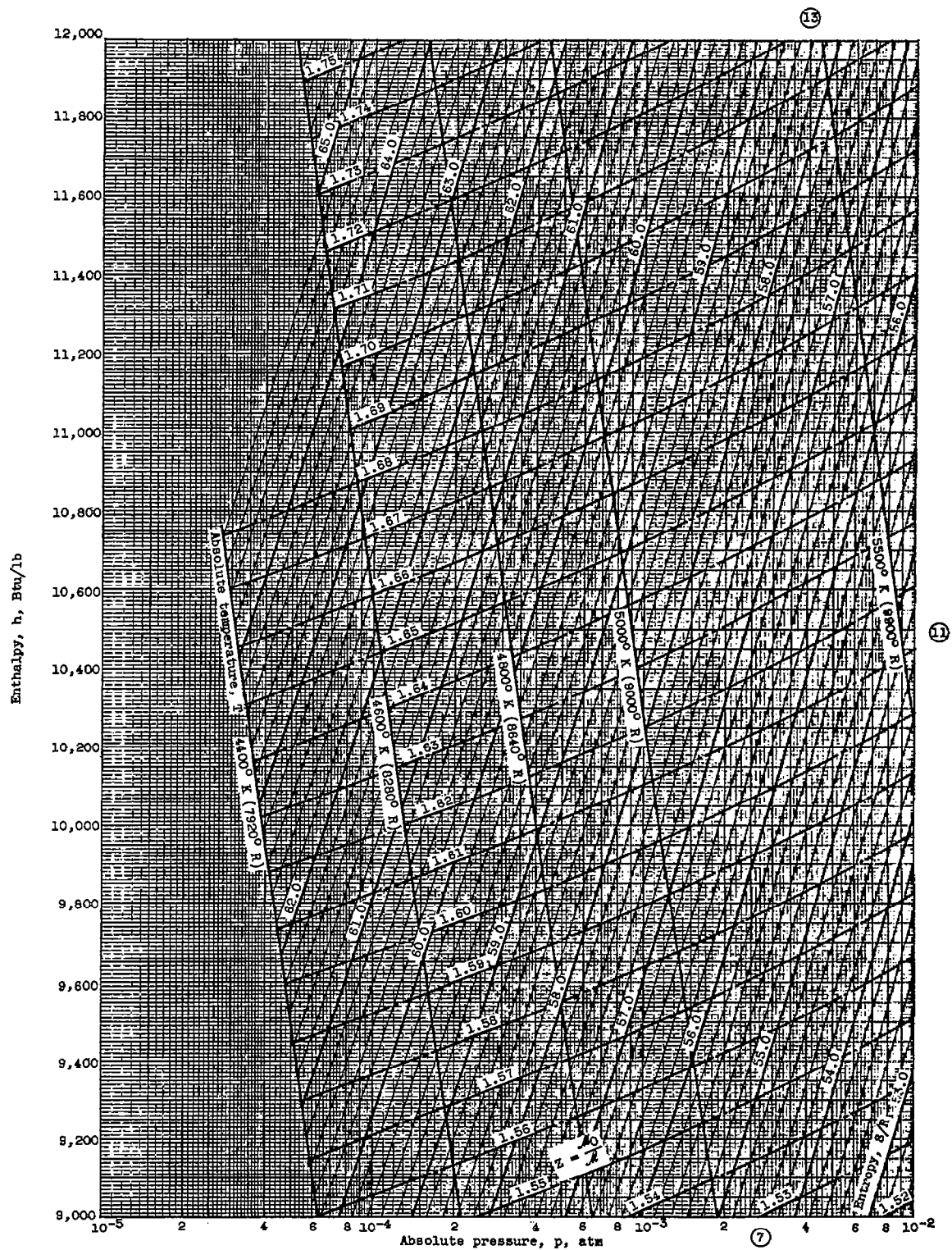
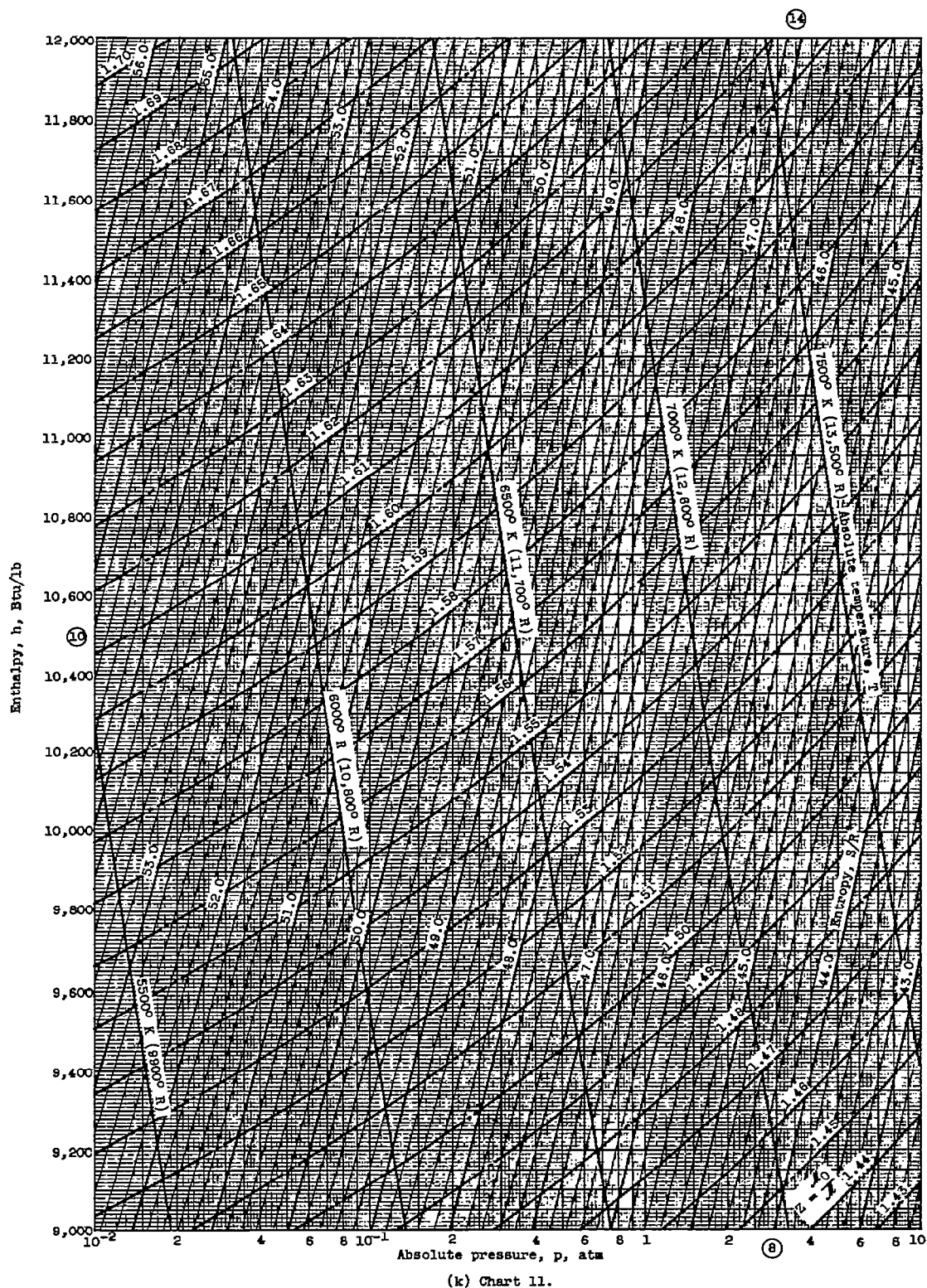


Figure 3. - Continued. Thermodynamic charts for air.

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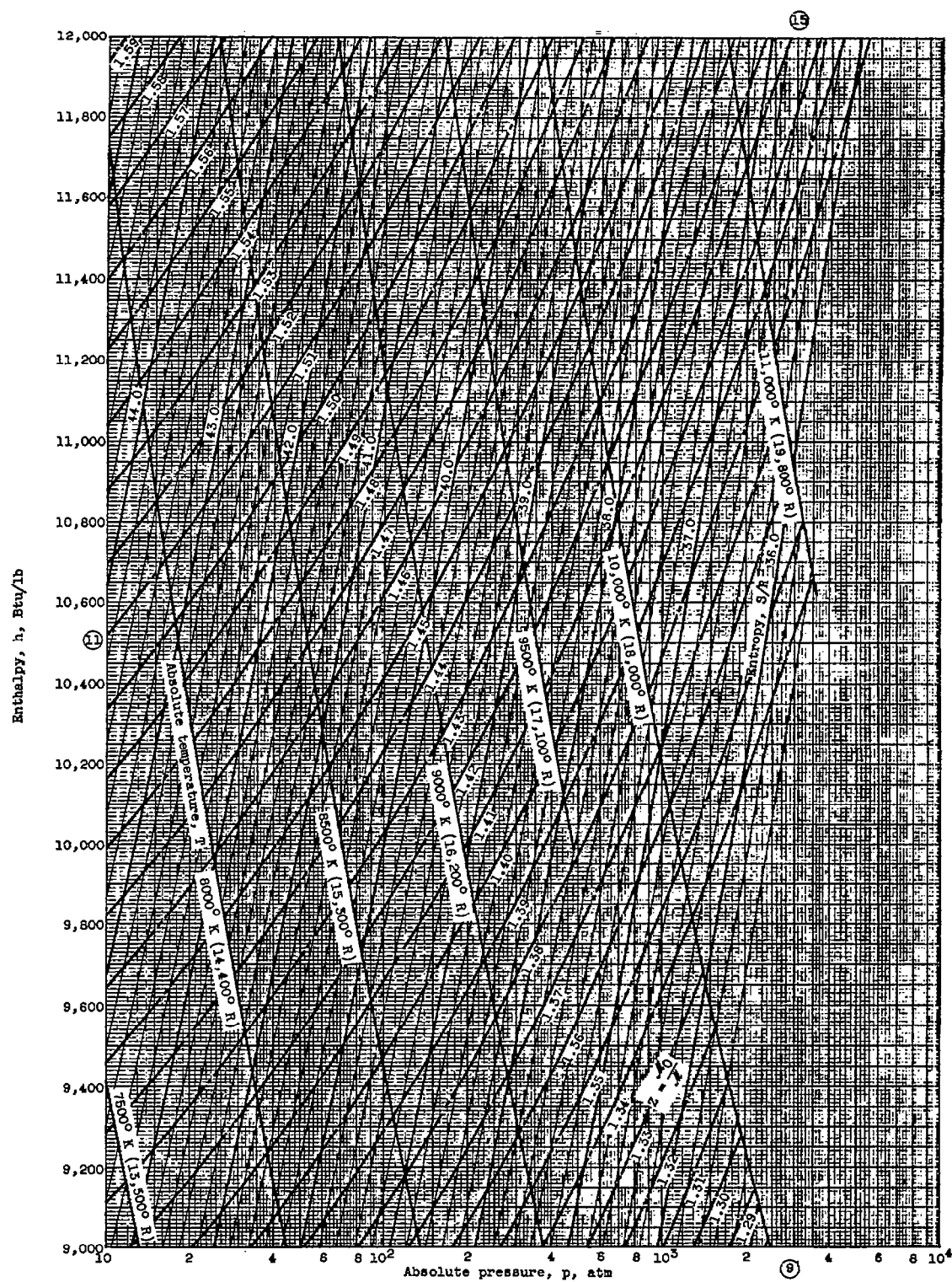


Figure 3. - Continued. Thermodynamic charts for air.

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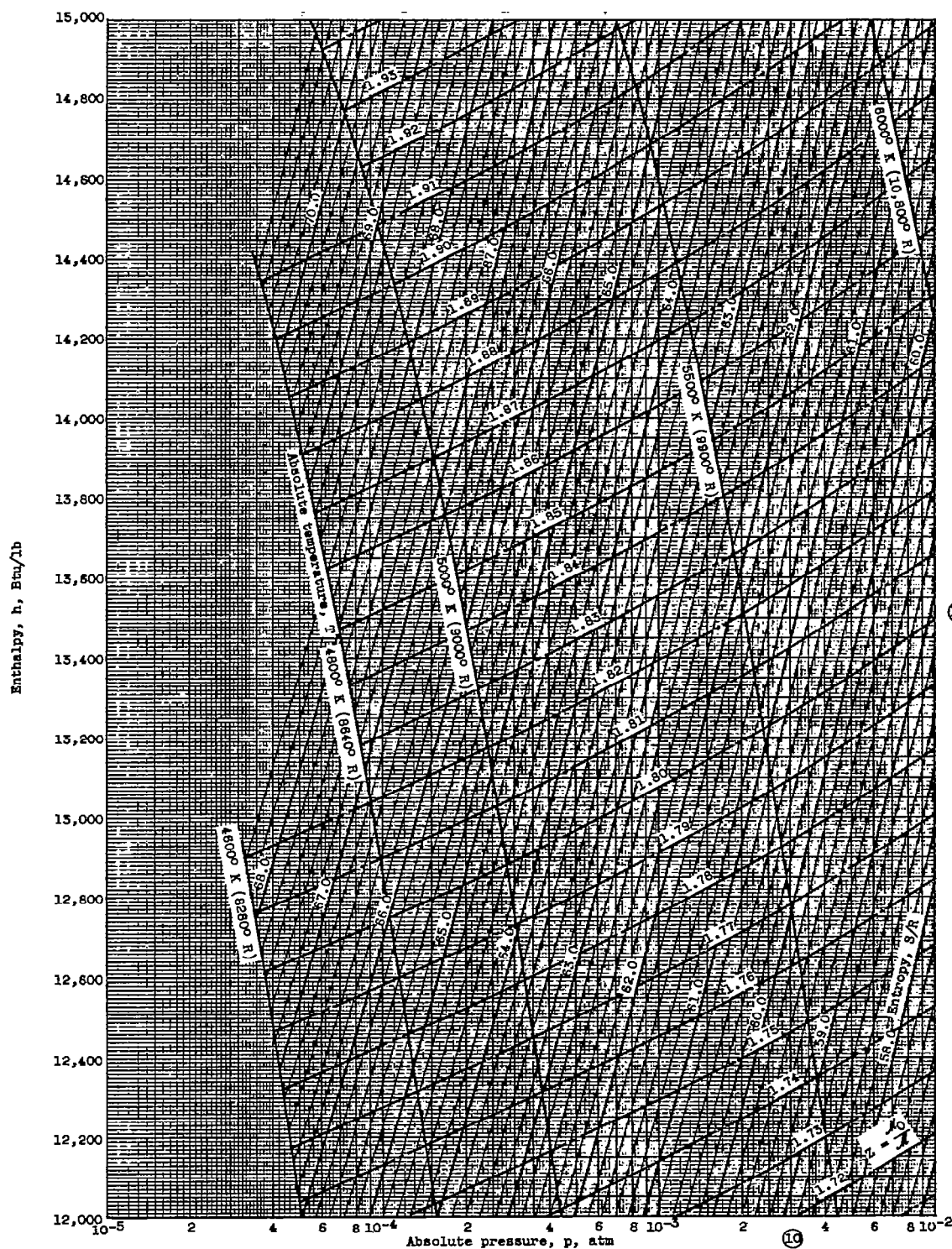


Figure 3. - Continued. Thermodynamic charts for air.

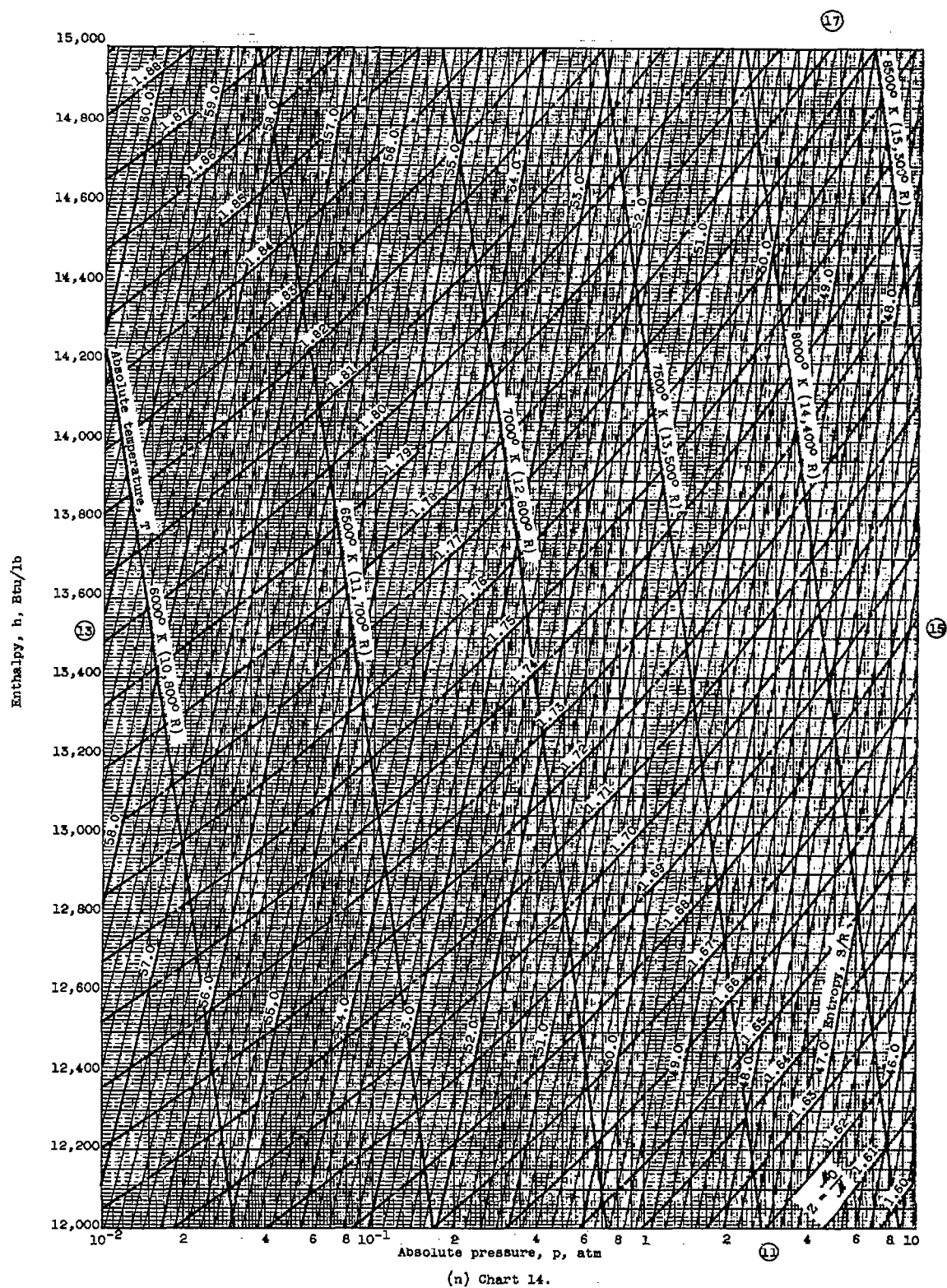


Figure 3. - Continued. Thermodynamic charts for air.

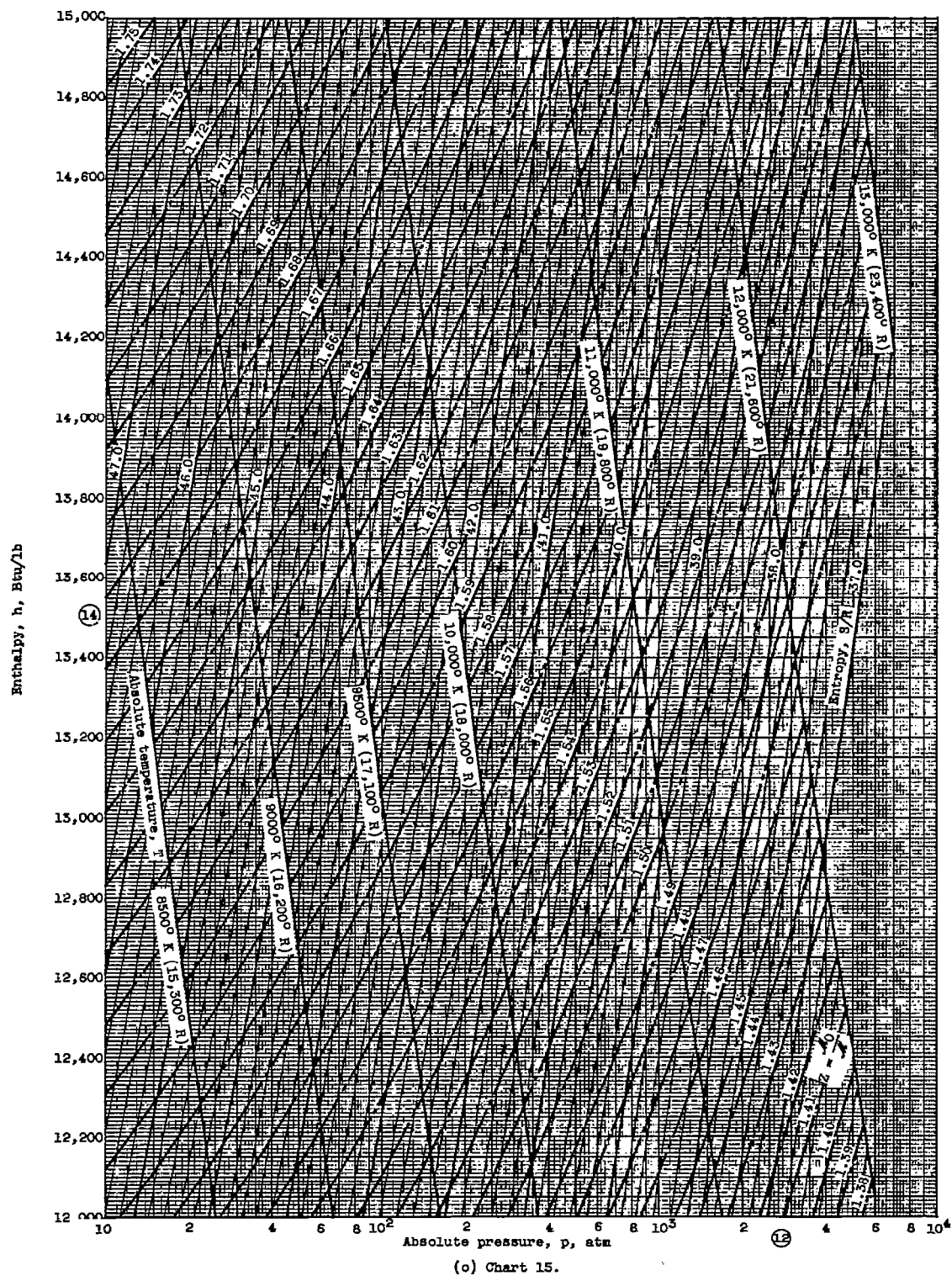
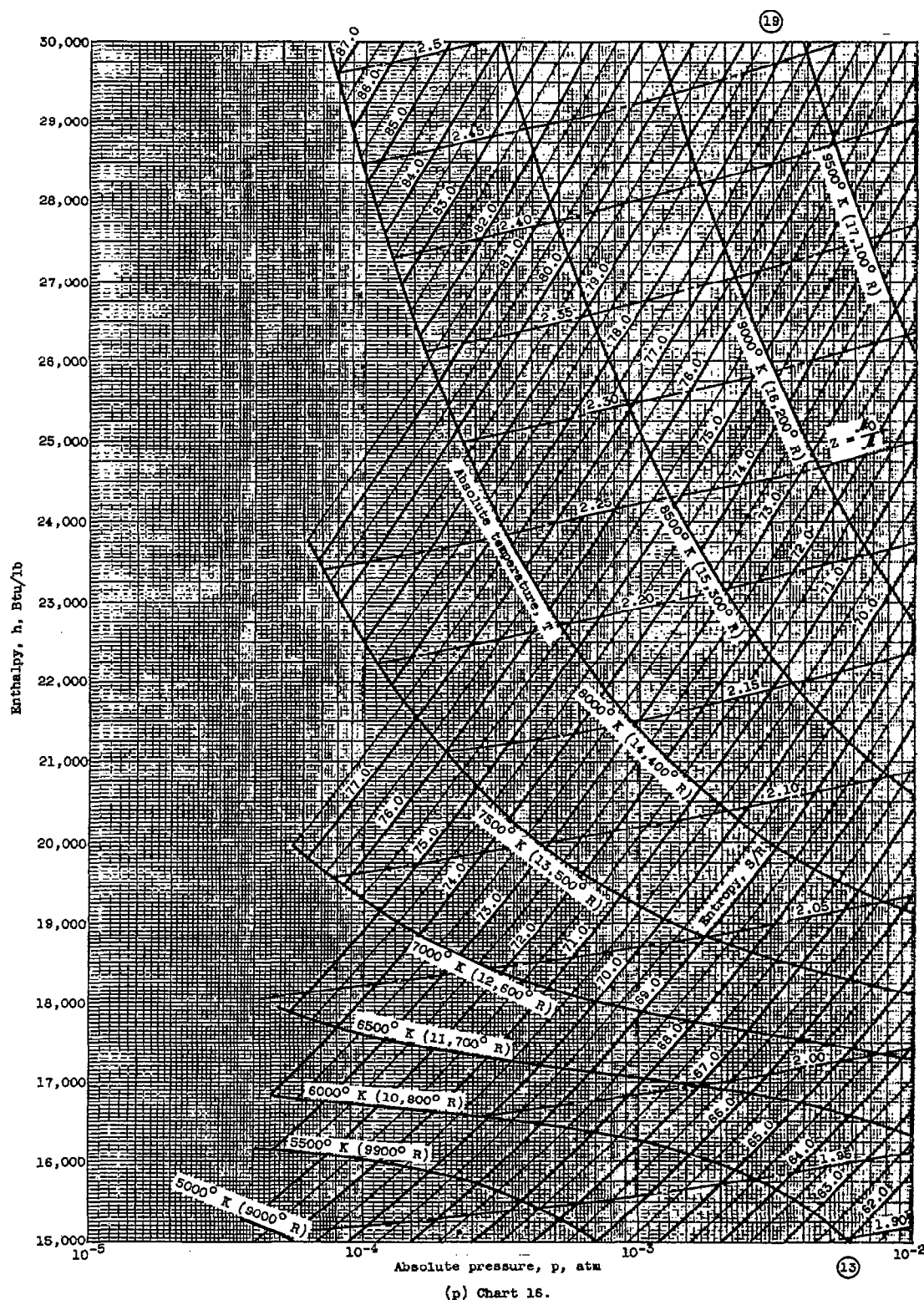
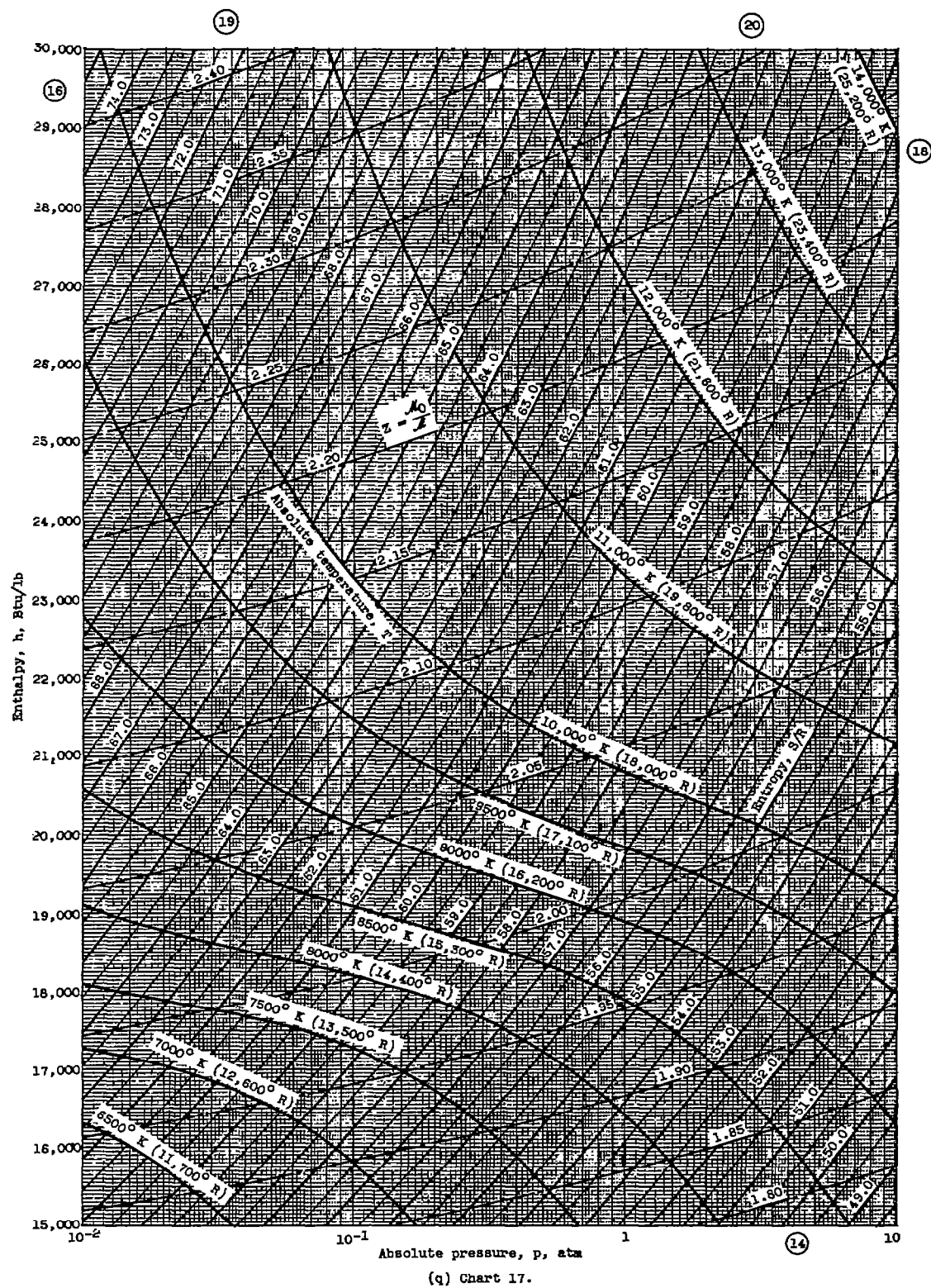


Figure 3. - Continued. Thermodynamic charts for air.





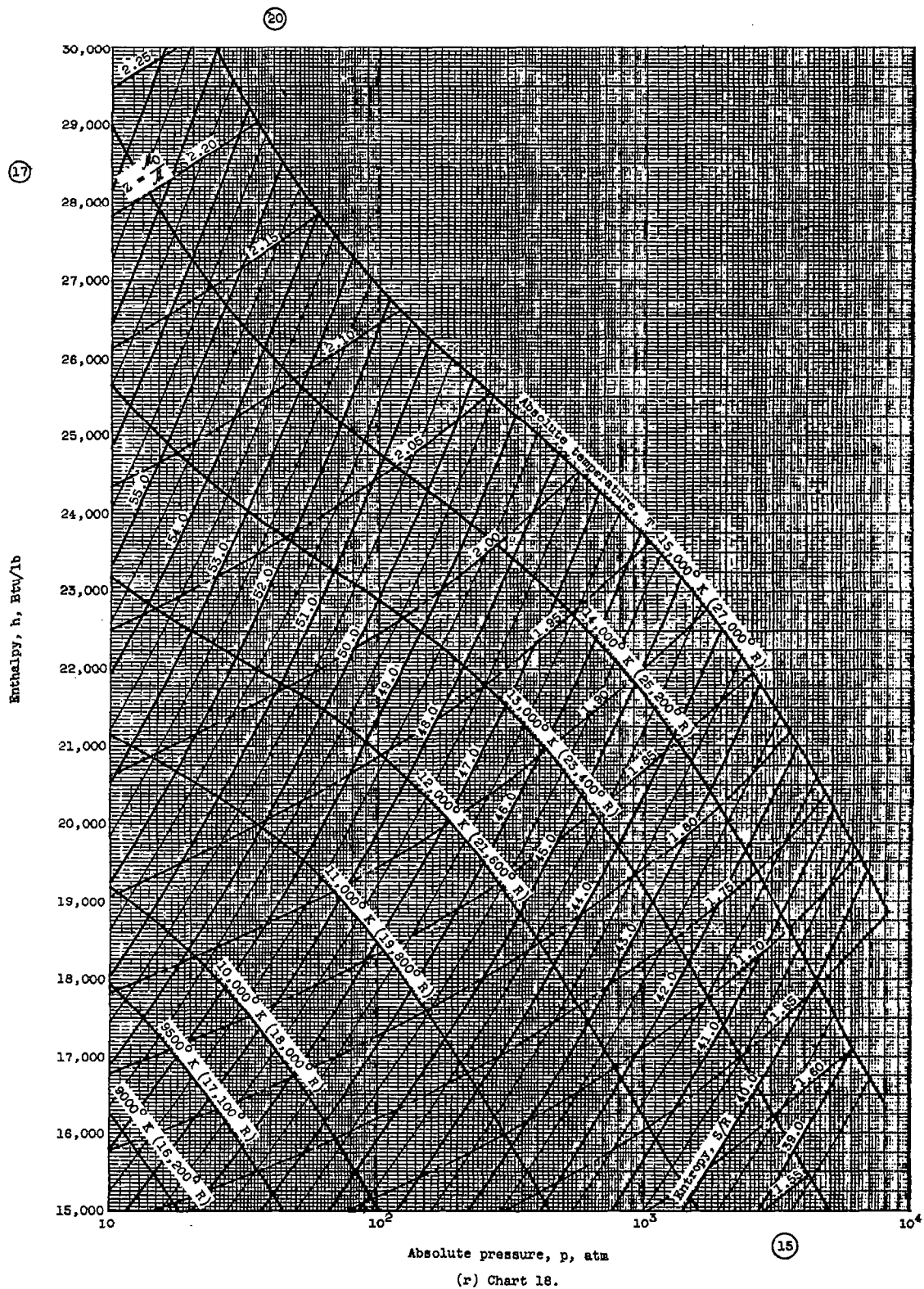
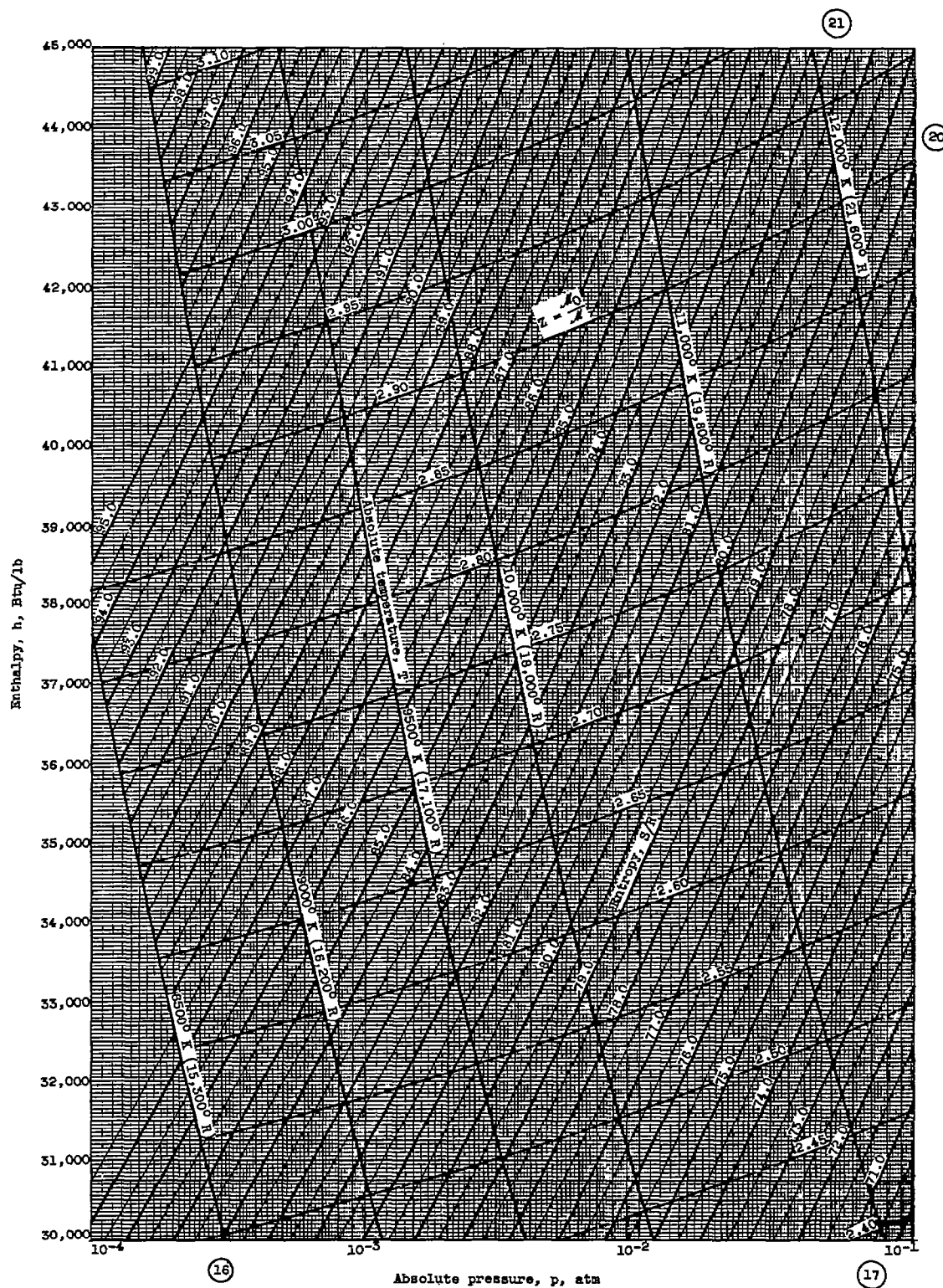


Figure 3. - Continued. Thermodynamic charts for air.

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Absolute pressure, p , atm

(s) Chart 19.

Figure 3. - Continued. Thermodynamic charts for air.

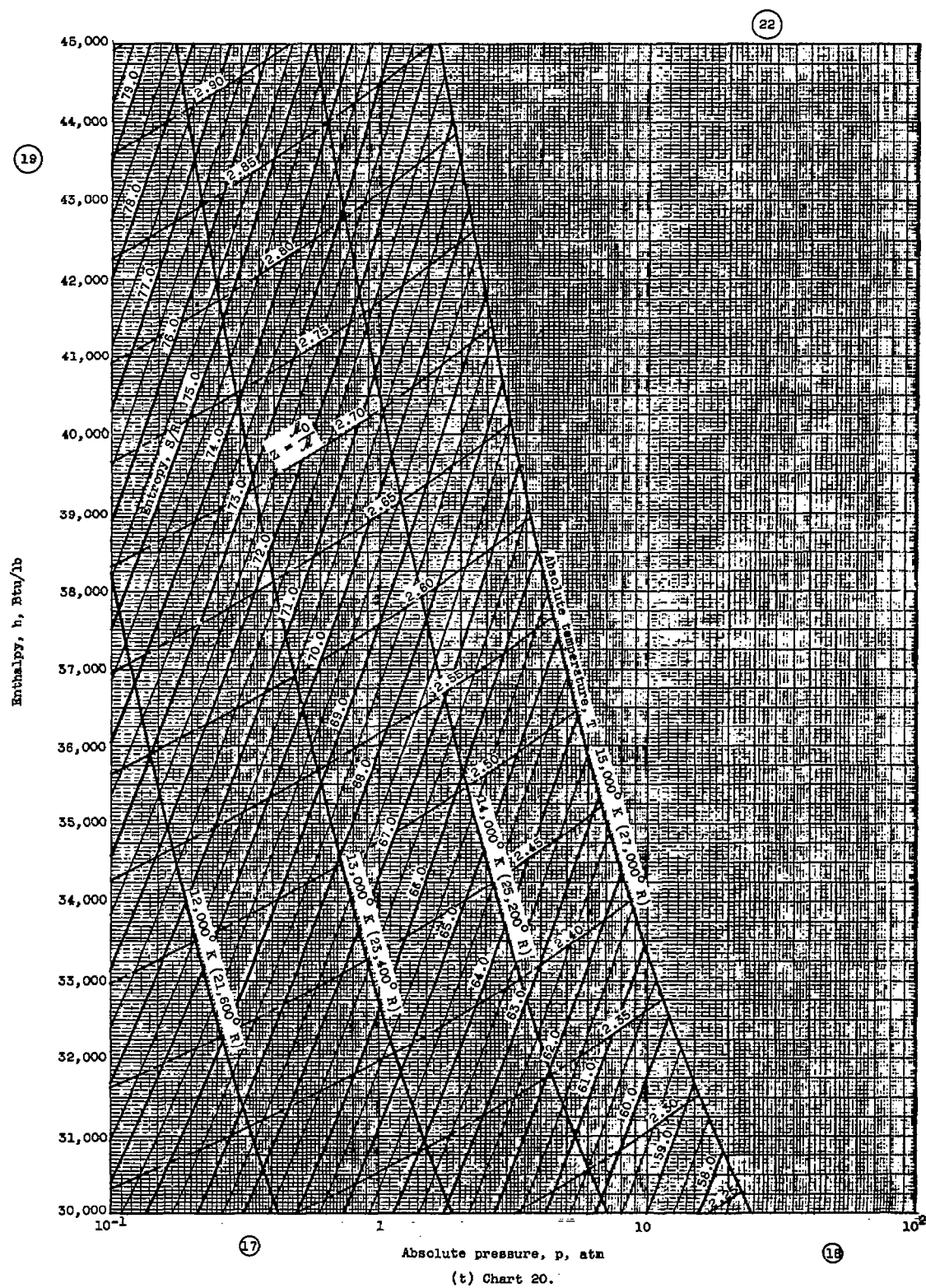
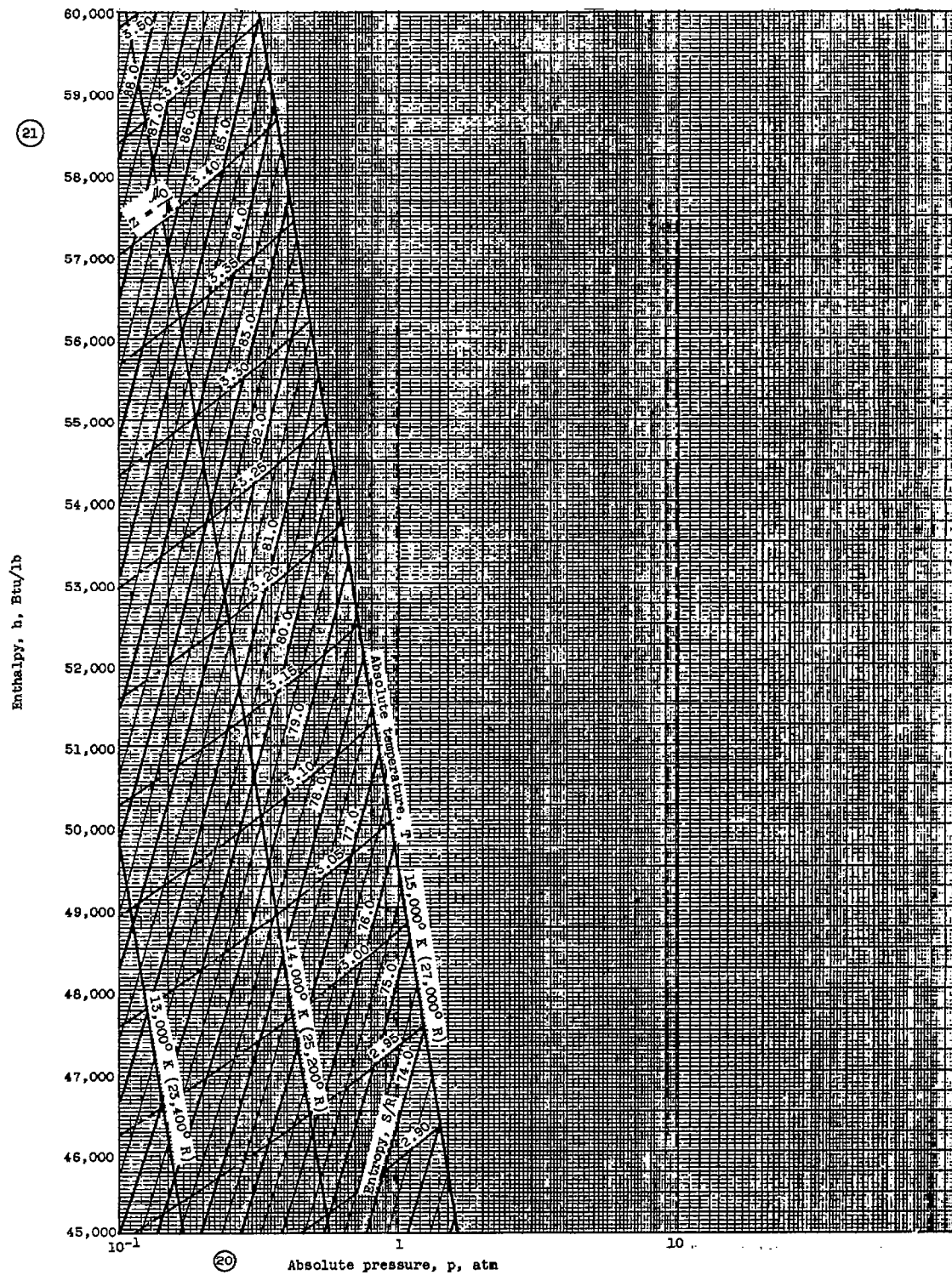




Figure 3. - Continued. Thermodynamic charts for air.



(v) Chart 22.

Figure 3. - Continued. Thermodynamic charts for air.

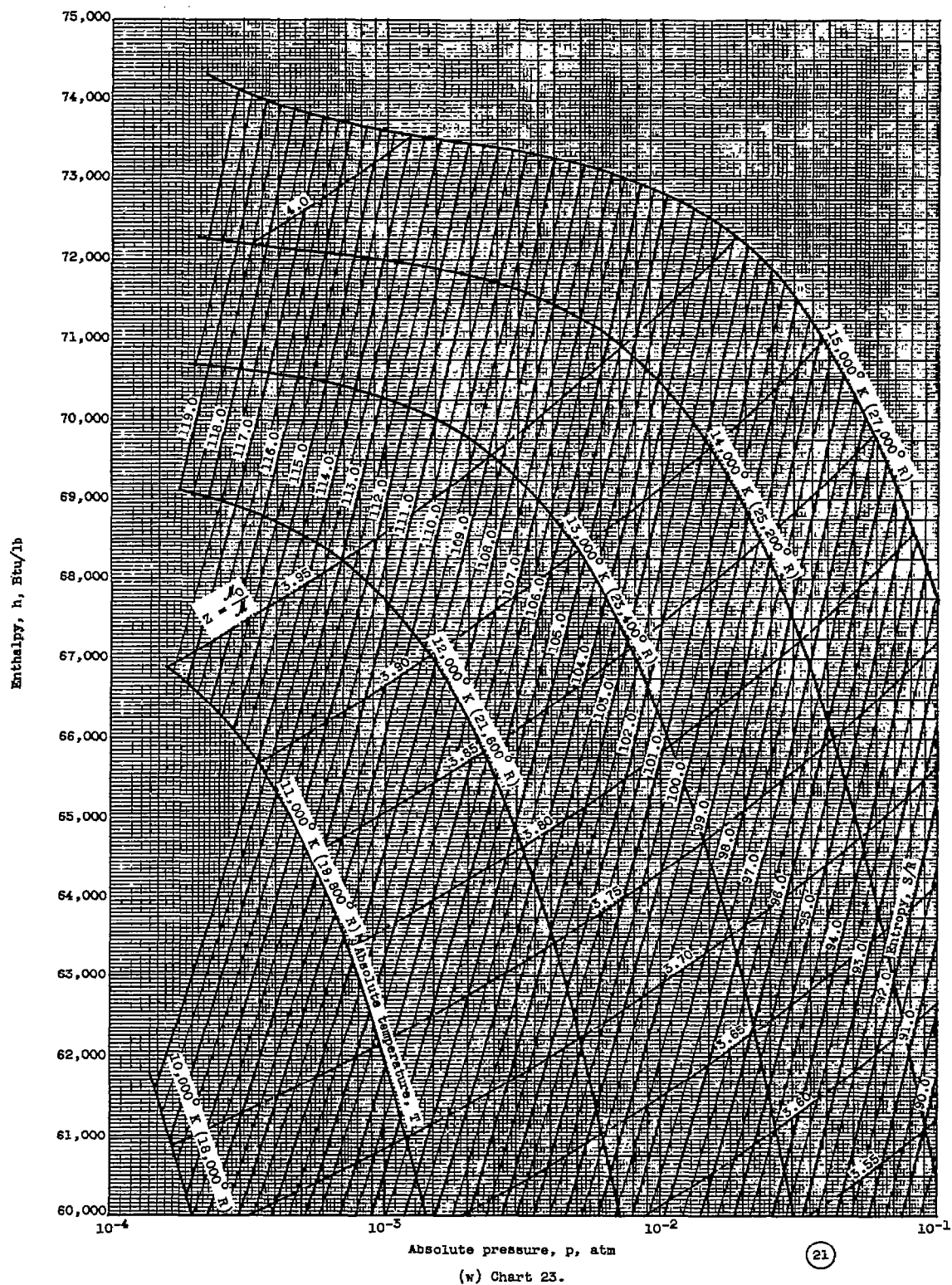


Figure 3. - Concluded. Thermodynamic charts for air.

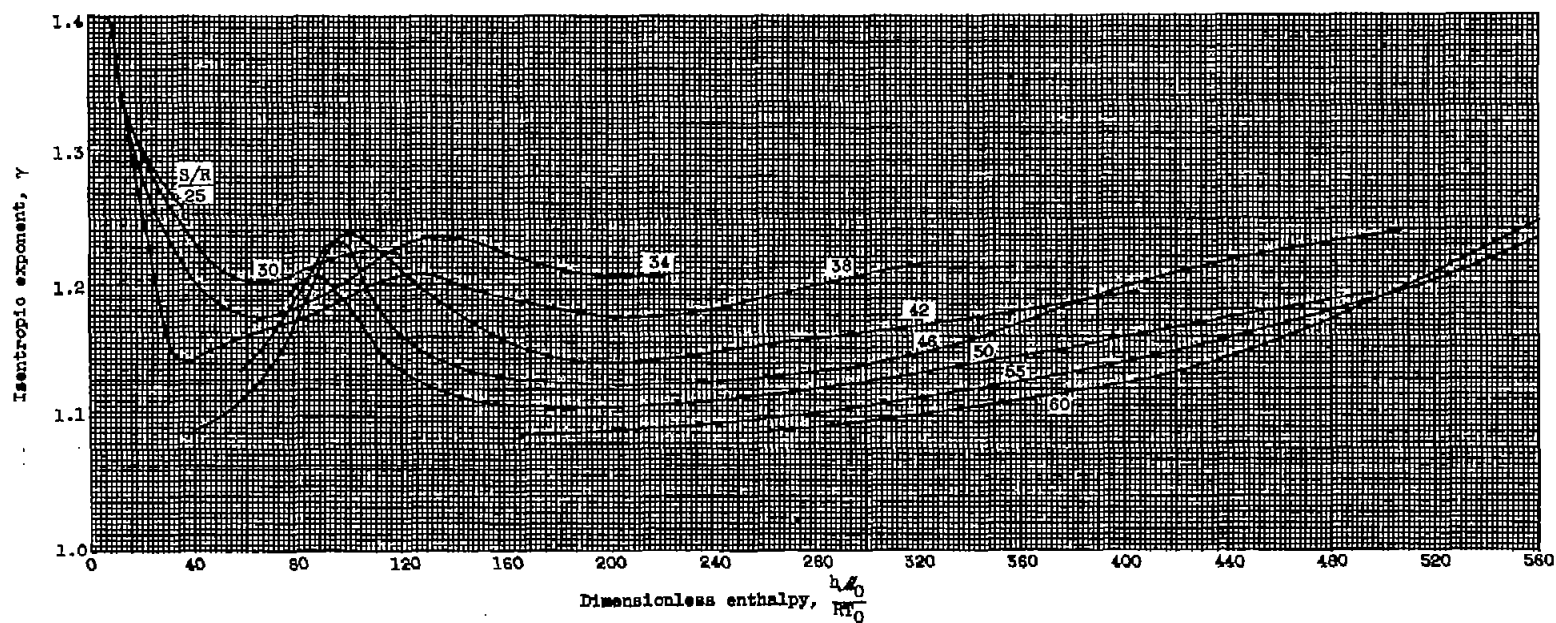


Figure 4. - Isentropic exponent for air in equilibrium.

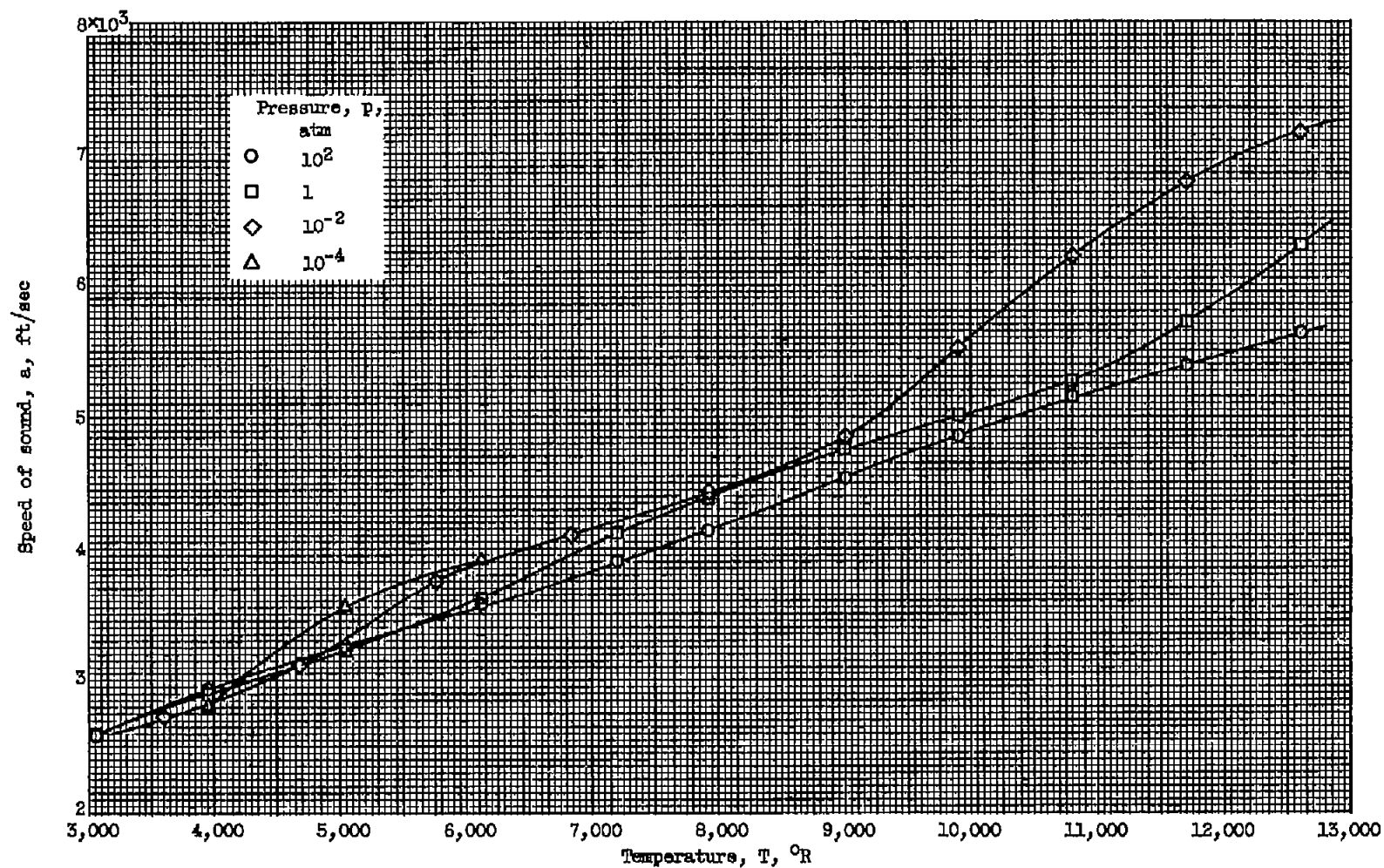


Figure 5. - Speed of sound in air against temperature. $a = \sqrt{\frac{\gamma R T}{M}}$.